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Panama Lakes Water Quality Modeling Study

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Final report

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ABSTRACT: The Panama Canal Authority operates the Panama Canal that connects the Atlantic and Pacific Oceans across the isthmus of Panama allowing for the passage of ocean-going vessels. The canal has a length of 80 km and is capable of traversing vessels up to 294 m long with maximum drafts of 12 m. Most portions of the canal are above sea level in a man-made reservoir, Gatun lake. The Canal, its associated reservoirs, and the lands adjacent to them are administered by the Panama Canal Authority (ACP). ACP is currently investigating the feasibility of expanding the canal system by constructing additional reservoirs to increase water availability for navigation. Currently, Gatun Lake and Lake Madden produce adequate quantities of water for navigation, power generation, and water supply. However, there is concern that an increase in the number of ships using the Canal in the future, coupled with drier conditions, could result in situations where there is inadequate water for canal operations. ACP is studying up to three new reservoirs to the west of Gatun Lake. The reservoirs of the western watershed are Río Indio, Caño Sucio, and Coclé del Norte (or Toabré). Waters from these reservoirs would be transferred via channel and tunnel to Gatun Lake. The purpose of this study was to assess what the expected water quality would be in the proposed reservoirs of the western watershed and what might occur due to interbasin water transfers from the proposed reservoirs to Gatun Lake with respect to the existing water quality. This report discusses the modeling results and offers conclusions and recommendations on the various scenarios simulated.

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Preface

This report summarizes the findings of a study conducted to simulate water quality in the existing and proposed reservoirs of the Panama Canal system. This study was performed by the U.S. Army Engineer Research and Development Center (ERDC), Waterways Experiment Station, Vicksburg, Mississippi, for Montgomery Watson Harza Global Inc. (MWH) under a Cooperative Research and Development Agreement (CRDA), Task Order 1, Project No. 15593 TO6/1001217. MWH was funded by the Panama Canal Authority (ACP) for the execution of this study. Appreciation is extended to Mr. Michael Newbery and Drs. Erich Brandstetter and C.Y. Wei of MWH for their assistance in this study. Appreciation is also extended to Agustin Arias, Jorge de la Guardia, and Roderick Lee of ACP, and John Gribar for their insight, assistance, and recommendations.

The two-dimensional, laterally averaged water quality model CE-QUAL-W2 (W2) was used in this study. This W2 application was developed using data supplied by ACP for Gatun Lake and Lake Madden. W2 was also set up for the proposed reservoirs of the western watershed, Río Indio, Caño Sucio, and Coclé del Norte (or Toabré). Scenario simulations were made for Río Indio to investigate water quality conditions in that reservoir and the potential for water quality impacts due to inter-basin transfers.

Principal Investigators for this study were Drs. Barry W. Bunch and Billy E. Johnson of the Water Quality and Contaminant Modeling Branch (WQCMB), Environmental Processes and Effects Division (EPED), Environmental Laboratory (EL), ERDC, and Ms. Maria S. Sarruff of the Coastal and Hydraulics Laboratory (CHL), ERDC. Drs. Bunch and Johnson conducted their portion of the study under the direct supervision of Dr. Mark S. Dortch, Chief, WQCMB, and under the general supervision of Dr. Richard E. Price, Chief, EPED, and Dr. Edwin A. Theriot, Director, EL. Ms. Sarruff conducted her portion of the study under the direct supervision of Mr. Thomas W. Richardson, Director, CHL.

COL John W. Morris III, EN, was Commander and Executive Director of ERDC. Dr. James R. Houston was Director.

1 Introduction

Purpose

This study was undertaken to assess what the expected water quality would be in the proposed reservoirs of the western watershed (Rio Indio, Cocle Norte, Caño Sucio), and what impacts might occur due to interbasin water transfers from the proposed reservoirs to Gatun Lake with respect to the existing water quality.

Objectives

The objectives of this study were:

a. Calibrate (with available data) CE-QUAL-W2 for Gatun Lake and Lake Madden.

b. Set up CE-QUAL-W2 for three proposed reservoirs: Rio Indio, Cocle Norte, Caño Sucio.

c. Simulate proposed reservoirs using calibrated CE-QUAL-W2 model to predict expected water quality within these reservoirs (per Scope of Work).

d. Simulate interbasin transfers from proposed reservoirs to Gatun Lake by considering various operating ranges, seasonal variations and operational scenarios that can provide high quality downstream water quality and transfer water for Gatun Lake that will not degrade the existing water quality (per Scope of Work).

Background

The Panama Canal Authority operates the Panama Canal which connects the Atlantic and Pacific Oceans across the isthmus of Panama allowing for the passage of ocean going vessels, Figure 1-1. The canal has a length of 80 kilometers and capable of traversing vessels up to 294 m long with maximum drafts of 12 m. Most portions of the canal are above sea level in a man-made reservoir, Gatun Lake. Gatun Lake was created by constructing a dam across the Chagres River approximately 13 kilometers upstream of its mouth with the Caribbean Sea.

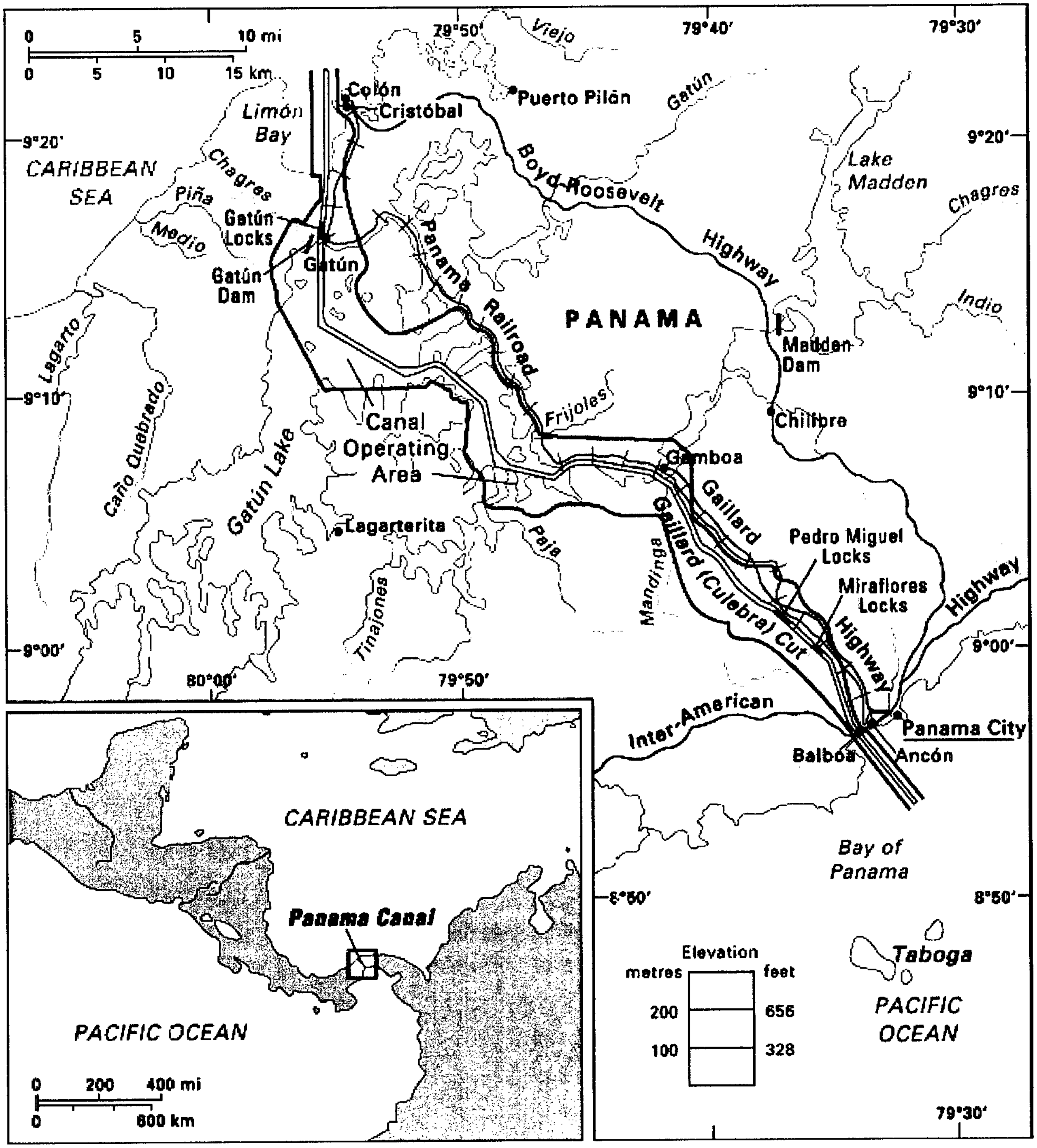

Figure 1-1. Panama Canal

Access to the canal is through a series of locks. Locks on each end of the canal have two lanes in order to facilitate two-way traffic. Gatun Locks, located on the Caribbean or Atlantic end of the canal are a set of three step locks. On the Pacific end of the canal, the Pedro Miguel Locks, a set of one step locks, connect Gatun Lake with Miraflores Lake, a body of water approximately 1.7 kilometers in length. At the other end of Miraflores Lake are the Miraflores Locks, a set of two step locks that connect the canal to the Pacific Ocean.

Construction of the Panama Canal began in the early 1900s and was completed in 1914. The Canal consisted initially of only Gatun Lake and the Atlantic and Pacific approaches and locks. Gatun Lake has a narrow operating range, 24.9-26.7 m (81.5-87.5 ft) above mean sea level, as its purpose is to facilitate navigation. It was not designed to allow for large fluctuations in water surface elevation and thus has only a limited capability to capture and store water. Excess water is spilled through Gatun Spillway to the sea. In 1935 Lake Madden was constructed in the Chagres River above Gatun Lake to increase water availability for navigation.

The Canal, its associated reservoirs, and the lands adjacent to them are administered by the Panama Canal Authority (ACP). The canal was built by the United States and administered by the Panama Canal Commission until the end of 1999 at which time the US formally handed complete control of the canal over to Panama. ACP is currently investigating the feasibility of expanding the canal system by constructing additional reservoirs to increase water availability for navigation. Currently, Gatun Lake and Lake Madden produce adequate quantities of water for navigation, power generation, and water supply. However, there is concern that an increase in the number of ships using the canal in the future coupled with drier conditions could result in situations where there is inadequate water for canal operations.

ACP is studying up to three new reservoirs to the west of Gatun Lake. The reservoirs of the western watershed are: Río Indio, Caño Sucio and Coclé del Norte (or Toabré). Waters from these reservoirs would be transferred via channel and tunnel to Gatun Lake. As the "Western Watershed" reservoirs do not exist, it is not possible to directly measure critical water quality parameters. However, it is possible to simulate the reservoirs of the Western Watershed and determine what their water quality would be and also what water quality impacts would be expected in Gatun Lake on an the existing water quality if waters from the Western Watershed were introduced into Gatun Lake.

Water quality is described as being "Good" in Gatun Lake and Lake Madden with the exception of localized degradation resulting from point source pollution. Water quality in the proposed reservoirs is unknown although a limited amount of tributary data has been and is being collected. A concern is that the water in the proposed reservoirs may be of poor quality and would have a detrimental impact when transferred to Gatun Lake. Since the proposed reservoirs are still under design, sampling can not address the question of their water quality or water quality impacts arising from inter-basin transfers.

Approach

One means of addressing the issue of water quality is by use of a numerical model. As stated in the Scope of Work, the CE-QUAL-W2 (W2), a state-of–the-art two-dimensional laterally averaged hydrodynamic and water quality model was applied for this task. W2 is well suited to simulating reservoir water quality incorporating all pertinent hydrodynamic and water quality processes where transverse (lateral) variations are insignificant. A more thorough description of W2 is contained in Chapter 4.

Application of W2 is separated into two distinct phases. The first phase is calibration of the model using a set of observed data from a known similar reservoir. The second phase is application of the calibrated model in a predictive role. As the proposed reservoirs do not exist and only the most basic information (size, operational range) are available it is not possible to "calibrate" W2 to them. Instead, W2 was calibrated to the existing reservoirs (Gatun Lake and Lake Madden) and the results of those calibrations used to set up W2 for the proposed reservoirs. Selection of Gatun Lake and Lake Madden as the source of calibration information for the proposed reservoirs was straightforward. Both reservoirs experience the similar meteorological conditions as the proposed reservoirs. Gatun Lake is immediately adjacent to the Western Watershed. Lake Madden is currently operated in a manner similar to what the reservoirs of the Western Watershed will be operated under, i.e., storage and discharge of water to Gatun Lake.

This interim report contains information of Lake Madden and Gatun Lake calibration. Also contained are the results from the first simulations for one of the proposed reservoirs, Río Indio. Additional simulations for Río Indio, and the remaining proposed reservoirs, Caño Sucio and Coclé del Norte (or Toabré). will be included in future addendums to this report.

2 Existing Reservoirs

Lake Gatun

Lake Gatun is the larger of the two reservoirs that make up the Panama Canal system. Lake Gatun was created by impounding the Rio Chagres approximately 13 km (8.1 miles) above its outfall into the Caribbean Sea. The maximum water surface elevation of Lake Gatun is 26.7 m (87.5 ft). Navigation between the Atlantic and Pacific Oceans is facilitated by sets of locks on the Caribbean and Pacific sides. Major tributaries to Lake Gatun are the Rio Chagres, Rio Trinidad, Rio Gatun, and Rio Ciri Grande. Numerous other smaller tributaries enter into the lake.

Physical description

The northern portion of Lake Gatun (Figure 1-1) is characterized by wide, deep areas created by flooding lowland plains. Depths in these areas often exceed 20 m even outside of the navigation channel. The southeastern portion of Lake Gatun is a narrow channel. One arm of Lake Gatun extends to the southwest towards the Rio Trinidad and Rio Ciri Grande tributaries. Along this arm, a portion of which is beyond the extent of the former canal zone, are several small villages and towns. At the western extent of this arm is the location to which diversion flows from the western watershed will be transferred.

The surface area of Lake Gatun is 436 km^2 and its total water volume is estimated to be 4944×10^6 m^3. Volume-elevation information is only available for the top 2 m (7 ft) of the reservoir. The normal operation range of Gatun Lake fluctuates over this 2 m range to guarantee the maximum ship draft of 12 m. The supplied volume-elevation information is based upon pre-impoundment surveys (Lee, 2001) and does not reflect any sedimentation that has occurred in the ensuing years. Shown in Figure 2-1 are the reported volume elevation curves for Lake Gatun and the volume-elevation relationship used in W2. As is evident there is substantial difference between the two curves in the zone where there is data. Two reasons are put forward for this.

First, the observed data is based upon pre-impoundment surveys and does not include any changes that have occurred due to sedimentation in the last ninety years. Estimates are, based upon experience with Madden that 10-12 percent of the difference could be attributable to sedimentation. The majority of the

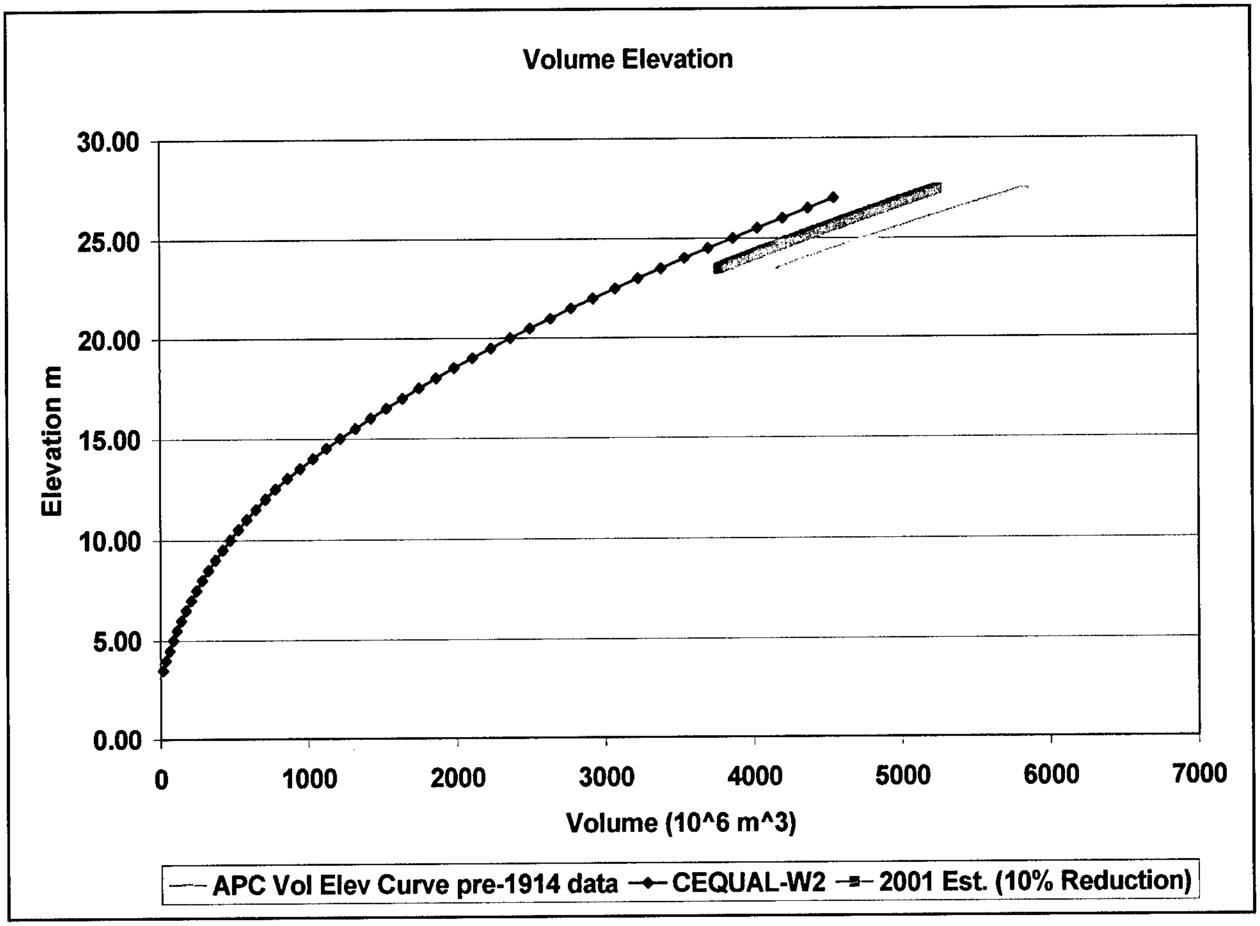

Figure 2-1. Gatun Lake volume-elevation information

Table 2-1
W2 Bathymetry Characteristics[1]

	Volume, 10^6 m^3	Area, 10^6 m^2	Average Depth, m
Whole Lake			
Gatun Lake	4,372.8	342.66	12.8
Individual Branches			
Branch 1	1,425	95.87	14.9
Branch 2	1,180	77.32	15.3
Branch 3	38.6	4.75	8.1
Branch 4	1,133.6	97.40	11.6
Branch 5	423.2	37.10	11.4
Branch 6	74.2	12.81	5.8
Branch 7	34.8	13.20	2.6
Branch 8	62.5	4.22	14.8

[1] For branch locations refer to Figure 5-4

difference is thought to have occurred prior to the construction of Madden Dam in 1935. After that time, Madden Lake served as a sedimentation trap for the Chagres River, Lake Gatun's largest tributary and should have decreased the sediment load to Gatun.

The second reason for the deviation between the reported volume elevation information and that of W2 is Lake Gatun's irregular shape. W2 simulates a body of water as stacks of quadrilateral blocks. The degree to which the quadrilaterals match the outline of the system directly impacts the degree to which the volume is captured. The reported bathymetry of Lake Gatun (Table 2-1), with its numerous bends and small embayments, is extremely difficult to match unless an excessively large number of segments are used. In addition, the lack of observed data below 23-m elevation hinders analysis of the W2 bathymetry to diagnose where any potential shortage may lie. While the volume elevation representation in W2 is lower that that reported, W2 does capture the major features in the system and that results obtained are not adversely affected.

Water quality characteristics

Significant tributaries to Lake Gatun are the Rio Chagres, Rio Trinidad, Rio Ciri Grande, and Rio Gatun. The major source of inflow is Rio Chagres whose inflow is controlled by Madden Dam. Additional sources of inflow include direct precipitation and ungaged runoff. Uses of Lake Gatun water are navigation, Municipal and Industrial (M&I) water supplies, and power generation.

Water quality in Lake Gatun remains at a sufficiently high level that little treatment is required for potable water. This condition has been characterized as "Good" (ACP, 2001). The last comprehensive data collection effort for Lake Gatun was conducted during the period 1972-1974. During that study, the water quality at most locations in system was very good. Study results indicated that water quality was good except for locations where there were discharges from canal support facilities or where tributaries contaminated with high waste loads (Rio Chilibre). In these instances, the depressed water quality conditions were localized to the area of the discharge. There were also locations outside the formal Canal Zone where water quality was depressed in waters adjacent to settlements. Development along the Transisthmian Highway has raised concerns that the possibility exists for additional degradation of Lake Gatun due to pollution in the watershed. However, water quality conditions at present are good enough that no additional treatment is required.

Hydrologic and meteorological characteristics

The tropical location of Lake Gatun results in there being no winter/summer seasonality. Instead, the year is divided into wet and dry seasons. The dry season is loosely defined as running from January through April, the wet season from May through December. Average rainfall rates for the Gatun gage for the period 1970-2000 are shown in Figure 2-2. Temperatures vary only slightly between the wet and dry seasons (Figure 2-3). Average dry season air temperature for the period 1985-2000 at the Gatun meteorological station was 26.8 °C (80.2 °F) and 26.7 °C (80.0 °F) for the wet season. Due to the close proximity of the equator, the period of daylight varies little throughout the year. Wind speed at the Gatun meteorological station during the dry season for the 1985-2000 period averaged

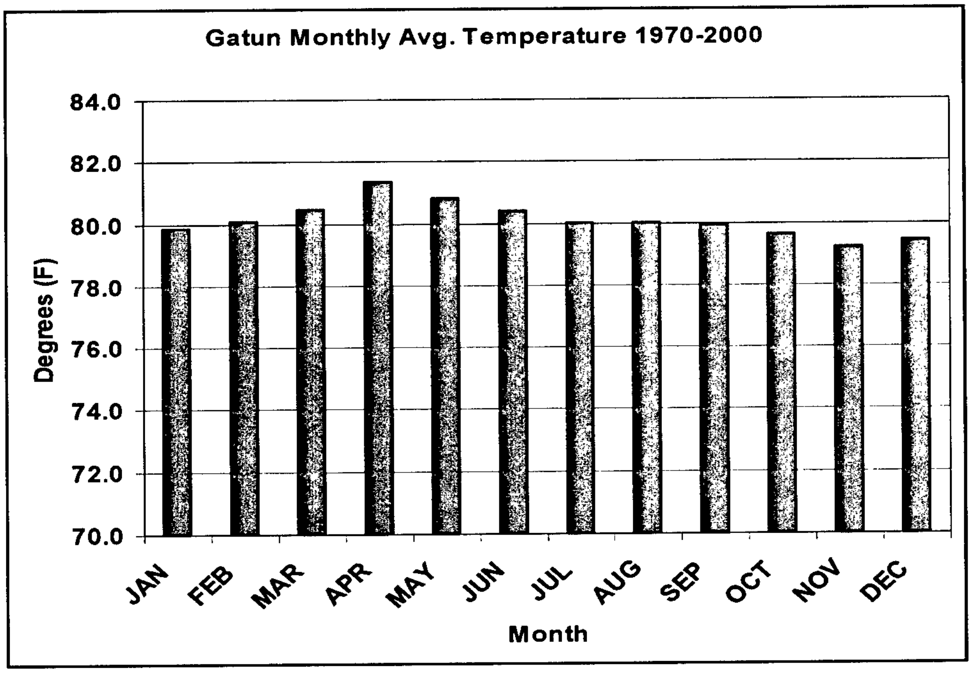

Figure 2-2. Average monthly air temperatures for Gatun meteorological station

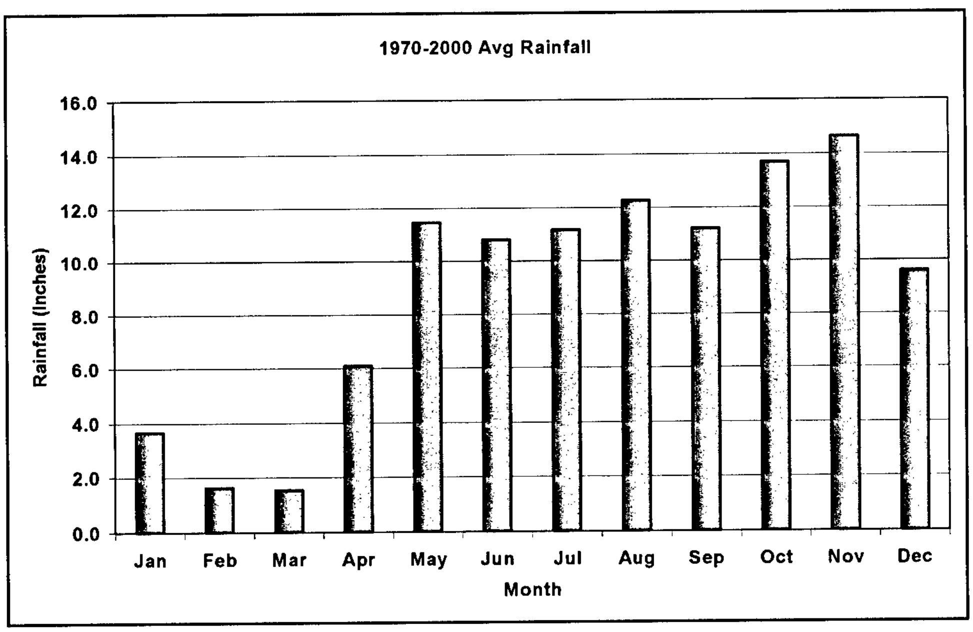

Figure 2-3. Average monthly rainfall for thirty-year period at Gatun Station

2.2 m/s (5.0 mph) and during the wet season 1.4 m/s (3.1 mph). Wind direction during the dry season was predominantly from the North. During the wet season, winds were more varied. In September and October winds are more southwesterly while during the remainder of the wet season they tend to be from the northwest.

Lake Gatun waters are used for power generation on a limited basis and only when there is excess water available. Power can be generated in the transfer of water from Lake Madden to Lake Gatun or by the passage of excess water through the Gatun Power Plant. In circumstances where there is not any excess water, power is not generated.

Lake Madden

Madden Lake runs approximate 19 km from north to south and is on average 2 km wide. The main river inflow is the Rio Chagres, which runs from east to west and enters Madden Lake in the lower portion of the lake. The upper portion of the lake is on average 10 meters deep while the lower portion, closer to the outlet, is on average 40 meters deep. The operational range of Lake Madden is from 58 m (190 ft) to 76.2 m (250 ft) above mean sea level.

Physical description

Shown in Figure 2-4 is the volume elevation curve for Lake Madden. Bathymetry data are primarily available as topographic maps, with some limited digital data from sediment range surveys. The development of model bathymetry files were done based upon manually digitizing available data.

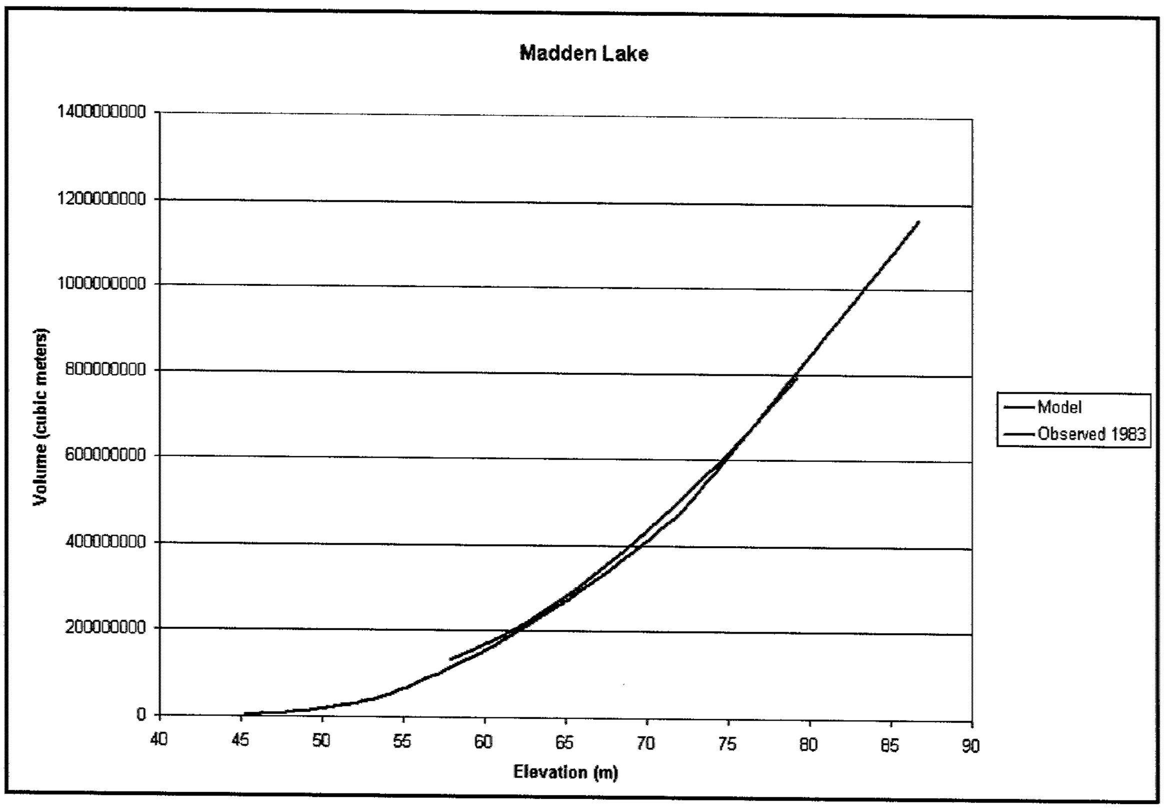

Figure 2.4. Madden Lake volume-elevation curve

Water quality characteristics

A number of water quality studies have been conducted over the past 30 years. The majority of these studies have been of short duration, for specific water quality constituents, and at specific locations. The only relatively comprehensive sampling study was conducted during the years 1972-1974. This study was not conducted to support any modeling effort. During that study, both in-pool concentrations and wastewater loadings were characterized. From the 1972-1974 study, all data available were reported as averages, maxima, and minima over the wet and dry seasons (Gonzalez et al. 1975).

Hydrologic and meteorological characteristics

For the Madden Lake model, the Chico, Candelaria, and Peluca discharge gages were used as inflows into branches 1, 2, and 4 respectively (Figures 2-5 and 2-6). In order to accurately model the water balance, additional inflow was introduced into branch 5 based upon data received from Montgomery-Watson-Harza (MWH) (i.e., Khalid's Inflows). The measured outflow, at the Madden Lake Dam, was used in the model to simulate water leaving Madden Lake and entering into Gatun Lake.

Monthly average meteorological data was available for both Gatun Lake as well as Madden Lake. The Gatun Meteorological Station was used for the Gatun Lake model while the Gamboa Meteorological Station was used for the Madden Lake model. For both the Gatun Meteorological Station and the Gamboa Meteorological Station, the period of record was 1985 to 2000, for the following variables: 1) Average Wind Direction; 2) Average Wind Speed; 3) Maximum Wind Speed; 4) Average Air Temperature; 5) Maximum Air Temperature; 6) Minimum Air Temperature; 7) Dew Point Temperature; 8) Average Relative Humidity; 9) Maximum Relative Humidity; 10) Minimum Relative Humidity; 11) Solar Radiation; and 12) Evaporation. For both gages, the monthly precipitation period of record was 1977 to 2000. Upon request, ERDC-EL did receive daily meteorological data (e.g. Average Air Temperature, Dew Point Temperaure, and Wind Speed) for 1988. Within the daily dataset, wind direction and cloud cover were not available, so monthly values of wind direction were used and estimated cloud cover values were used in the simulations.

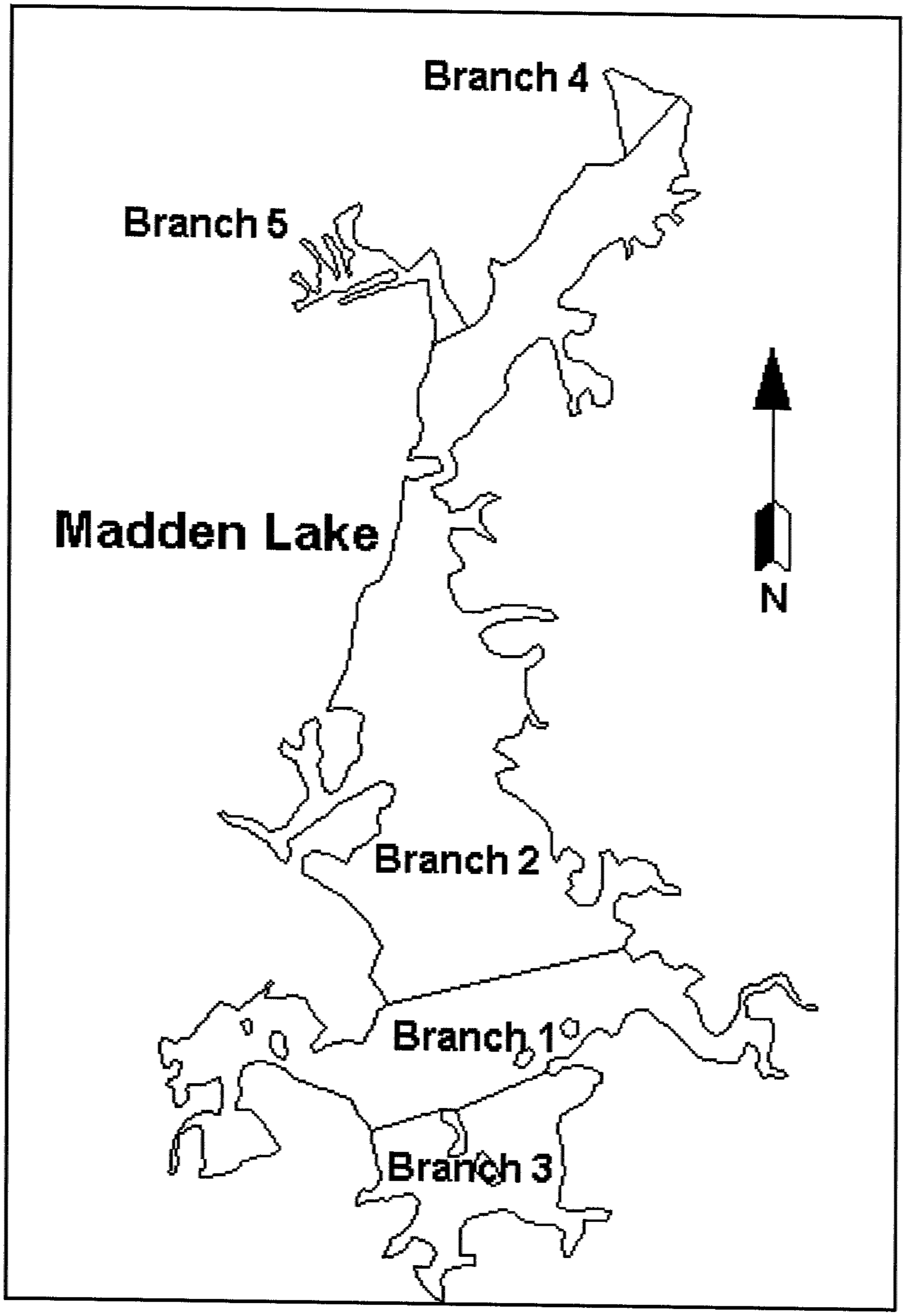

Figure 2-5. Madden CE-QUAL-W2 branches

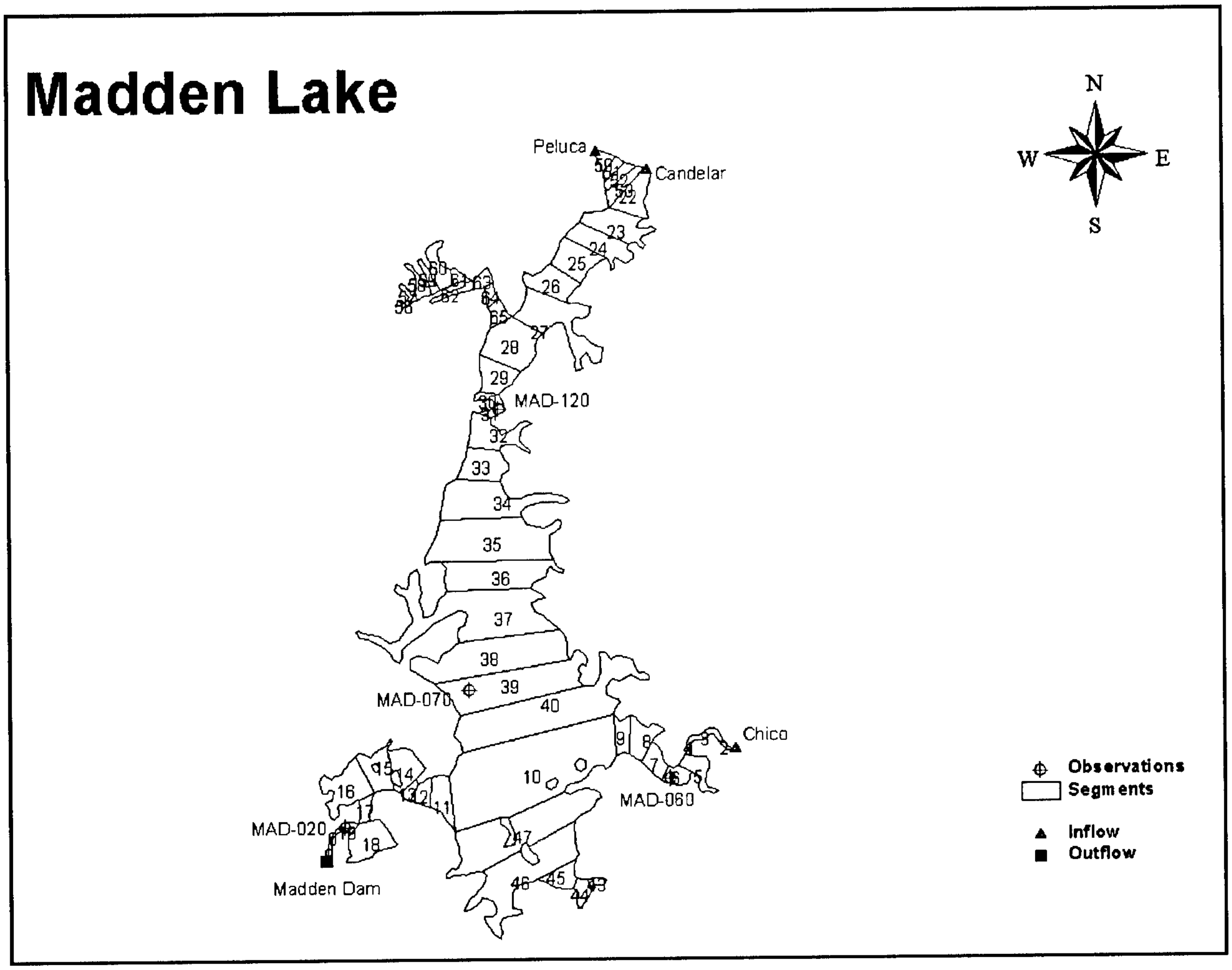

Figure 2-6. Madden CE-QUAL-W2 segments

3 Databases

Data Requirements

Numerical modeling requires a large variety of information in order to completely describe a systems behavior. Among the information required are a mathematical description of the system geometry, information on inflows quantity and quality, characteristics of the water in the system, important loading sources, meteorological information, and reservoir operational data.

1972-1974 water quality data

No data collection effort was conducted during this study for the purposes of model calibration. As stated in the Scope of Work, existing data from a comprehensive water quality sampling study spanning the period 1972-1974 were used. These data, consisting of seasonal averages and extremes, are reported in Appendix E of that study (Gonzalez et al. 1975). An attempt was made to obtain the actual observations in addition to the summaries contained in Appendix E. It was determined that the individual observations no longer existed and the only record of the sampling study was the 1975 report.

Use of such an old data base with inconsistent data sets for calibration is unusual and unwarranted in most cases. However, the 1972-1974 sampling effort was very thorough in its spatial extent in Lakes Gatun and Madden. In addition, much of the watershed remains undeveloped due to its location in the Canal Zone under the jurisdiction of the U.S. Panama Canal Commission and now the Panamanian ACP. Communities along the shores of Lakes Gatun and Madden are small and point source dischargers are limited. Development along the Transisthmian Highway, which is outside of the old Canal Zone Boundaries but still in the watershed, has been substantial since the 1975 sampling report (Smithsonian 1999). Organic and nutrient loadings from this area are a significant source of pollution in the smaller tributaries entering Lake Gatun. However, water quality has not been impacted enough in Lake Gatun or Lake Madden to warrant additional treatment at the potable water treatment plants. Consequently, there is reason to believe that the fundamental water quality conditions observed in 1972 are similar to those existing today and that the data from the 1972-1974 period are representative of the conditions that exist today. However, a well designed monitoring program is required to verify this hypothesis since the forcing condition data sets are not consistent with the water quality data sets.

However, this hypothesis should be verified by a well-designed monitoring program in which all of the data required for a modeling study are collected.

During the period 1972-1974 111 stations were sampled in Lake Gatun and 17 in Lake Madden. For each station, some of the parameters in Table 3-1 were determined. Not all stations reported the same parameters. Not contained in the report are the dates of each station's sampling events nor the number of times that the station was sampled. Unless otherwise indicated, all data were taken as representing mid-water column conditions. Many of the samples during the 1972-1974 study yielded results that were below the analytical detection limits available at that time. This was a further indication of the favorable water quality throughout the system at that time.

Missing from the 1972-1974 report are observations for chlorophyll. Consequently, no information on algal levels in Lakes Gatun or Madden were available. Algae have significant impacts upon overall water quality. Algae take up nutrients and release organic material and dissolved oxygen. At high levels, algae can detrimentally impact water quality. Based upon Sechi depth observations from 1972-1974, it did not appear that excessive algal levels were widespread in Lake Gatun or Madden. Secchi depths at numerous stations were quite large which indicates a high level of water transparency. The presence of algae would diminish transparency and clarity.

Significant waste loads in the canal watershed were also characterized during the 1972-1974 sampling program. The majority of these loads were not in the current study area. Only two significant loads were determined to be in Lake Gatun. One was the outfall at Gamboa and the other the USNS Summit outfall. Flows from these sites were small in comparison to tributary flows. However, the high concentrations of nutrients and other substances in the discharges resulted in the loads from these two sites being significant. Samples had been collected from these discharges and analyzed for the same parameters being sampled for in the water column. Waters around these sites were also extensive sampled to determine the extent of elevated coliform levels due to the discharges.

Inflows and outflows

Four significant tributaries empty into Lake Gatun. They are the Chagres River, Rio Trinidad, Rio Ciri Grande, and Rio Gatun. Flows records are available for all four for the periods shown in Table 3-1. In addition there are lesser ungaged tributaries mainly in the eastern and southern portions of the watershed which contribute flow. The Chagres, whose flow is controlled by Madden Dam, is the largest source with an average flow for the years 1966-2000 averaging 71.8 m^3s (2534 cfs).

Waters are removed from Lake Gatun for the purposes of navigation, water supplied, power generation, and spillway spillage. Historical rates for these three uses are shown in Table 3-2. Navigation occurs year round and is the highest priority use of Lake Gatun waters. On average almost twice the amount of water has been used for navigation as has been used for generation. Power generation is

Table 3-1
Gaged Tributary Inflows to Lake Gatun

Tributary	Average Q m^3/s (cfs)	Years
Chagres below Madden Dam	71.81 (2534)	1966-2000
Rio Gatun	8.95 (316)	1971-2000
Rio Ciri Grande	9.09 (321)	1978-2000
Rio Trinidad	7.06 (249)	1971-2000

Table 3-2
Average Annual Gatun Outflows 1966-1999

Withdrawal	Flow m^3/s (cfs)
Generation	43.90 (1549)
Gatun Locks(Atlantic)	41.18 (1453)
Pedro Miguel Locks (Pacific)	40.33 (1423)
Spillage	22.13 (781)
Water Intakes (1995-1999)	3.54 (125)

not a scheduled event but occurs only when there is excess water available beyond navigation, and M&I requirements.

Lake Gatun with a surface area of 436 km^2 occupies 18.9 percent of the watershed below Lake Madden. As such a large portion of the watershed is covered by the reservoir itself, and due to Lake Gatun's tropical location, direct rainfall is a critical component of the water balance for Lake Gatun. Data for the meteorological station at Gatun indicate an average of 107.9 inches of rain fell directly on Lake Gatun each year for the period 1971-2000. This rainfall is equivalent to a continuous inflow of 38 m^3/s (1341 cfs). Evaporation is also a significant component of the water balance accounting for average losses of 40.2 inches/year based on 1971-2000 data. This rate is equivalent to a continuous discharge of 14 m^3/s (499.5 cfs).

Total measure inflow for Lake Gatun including estimated direct rainfall is less than the reported outflows. Consequently, this is an indication that a component of the overall water balance is ungaged. This "missing flow" is representative of direct runoff from the shores of Lake Gatun, inflow of ungaged tributaries and the net impact of direct rainfall.

Meteorological data

Monthly historical records for the Gatun, Gamboa, and FAA Summit stations were obtained. Included in these records were the information listed in Table 3-3. The period of record for the data listed in Table 3-3 was 1985 to present with the exception of the rainfall data. Rainfall records at Gatun began in 1905 and at Gamboa in 1881.

Table 3-3
Monthly meteorological data

Average Wind Speed	**Average Dewpoint Temperature**
Average Wind direction	Average Relative Humidity
Average Air Temperature	Maximum Relative Humidity
Maximum Air Temperature	Minimum Relative Humidity
Minimum Air Temperature	Total Solar Radiation
Total Monthly Rainfall	Total Evaporation

4 W2 Formulation

Contained here is a general overview of CE-QUAL-W2 obtained from the CE-QUAL-W2 users guide, (Cole and Buchac 1975). A more complete documentation including equations and rates can be found in that manual. Some of the information in this Chapter may not be applicable to the current Panama Lakes application but is included to illustrate the model's capabilities in the event that additional data are obtained.

CE-QUAL-W2 was selected for this study by ERDC because W2's 2-D width averaged hydrodynamic and water quality simulation approach is most suitable for modeling the Panama Canal system including Gatun Lake and the proposed reservoirs. W2 is widely used for reservoir and estuarine modeling studies by the CORPS, other Federal Agencies, States, consultants, and others. Being that CE-QUAL-W2 is developed primarily for use in simulating reservoirs, it has many features required for reservoir simulations that are not found in standard estuarine models.

Model Overview

CE-QUAL-W2 is a two-dimensional, width-averaged, longitudinal/vertical, hydrodynamic and water quality model. Because the model assumes lateral homogeneity, it is best suited for relatively long and narrow waterbodies exhibiting longitudinal and vertical water quality gradients. The model has been applied to rivers, lakes, reservoirs, and estuaries.

The application of CE-QUAL-W2 requires knowledge in the following areas:

a. Hydrodynamics.

b. Aquatic biology.

c. Aquatic chemistry.

d. Numerical methods.

e. Computers and FORTRAN coding.

f. Statistics.

g. Data assembly and reconstruction.

Model Background

CE-QUAL-W2 has been under continuous development since 1975. The original model was known as LARM (***L**aterally **A**veraged **R**eservoir **M**odel*) developed by Edinger and Buchak (1975). The first LARM application was on a reservoir with no branches. Subsequent modifications to allow for multiple branches and estuarine boundary conditions resulted in the code known as GLVHT (***G**eneralized **L**ongitudinal-**V**ertical **H**ydrodynamics and **T**ransport* Model). Addition of the water quality algorithms by the Water Quality Modeling Group at the U.S. Army Engineer Waterways Experiment Station (WES) resulted in CE-QUAL-W2 Version 1.0 (Environmental and Hydraulic Laboratories 1986).

CE-QUAL-W2 Version 2.0 is a result of major modifications to the code to improve the mathematical description of the prototype and increase computational accuracy and efficiency. Numerous new capabilities have been included in Version 2.0. These are:

a. An algorithm that calculates the maximum allowable timestep and adjusts the timestep to ensure hydrodynamic stability requirements are not violated (autostepping).

b. A selective withdrawal algorithm that calculates a withdrawal zone based on outflow, outlet geometry, and upstream density gradients.

c. A higher-order transport scheme (QUICKEST) that reduces numerical diffusion (Leonard, 1979).

d. Time-weighted vertical advection and fully implicit vertical diffusion.

e. Step function or linear interpolation of inputs.

f. Improved ice-cover algorithm.

g. Internal calculation of equilibrium temperatures and coefficients of surface heat exchange or a term-by-term accounting of surface heat exchange.

h. Variable layer heights and segment lengths.

i. Surface layer extending through multiple layers.

j. Generalized time-varying data input subroutine with input data accepted at any frequency.

k. Volume and mass balances to machine accuracy.

l. Sediment/water heat exchange.

Capabilities

Hydrodynamic

The model predicts water surface elevations, velocities, and temperatures. Temperature is included in the hydrodynamic calculations because of its effect on water density.

Water quality

The water quality algorithms incorporate 21 constituents in addition to temperature including nutrient/phytoplankton/dissolved oxygen (DO) interactions during anoxic conditions. Any combination of constituents can be simulated. The effects of salinity or total dissolved solids/salinity on density and thus hydrodynamics are included only if they are simulated in the water quality module. The water quality algorithm is modular allowing constituents to be easily added as additional subroutines.

Long term simulations

The water surface elevation is solved implicitly which eliminates the surface gravity wave restriction on the timestep. This permits larger timesteps during a simulation resulting in decreased computational time. As a result, the model can easily simulate long-term water quality responses. Version 3.0 will eliminate the diffusion criteria from stability requirements allowing for even larger timesteps.

Head boundary conditions

The model can be applied to estuaries, rivers, or portions of a waterbody by specifying upstream or downstream head boundary conditions.

Multiple branches

The branching algorithm allows application to geometrically complex waterbodies such as dendritic reservoirs or estuaries.

Variable grid spacing

Variable segment lengths and layer thicknesses can be used allowing specification of higher resolution where needed.

Water quality independent of hydrodynamics

Water quality can be updated less frequently than hydrodynamics thus reducing computational requirements. However, water quality kinetics are ***not*** decoupled from the hydrodynamics (i.e., separate, standalone code for hydrodynamics and water quality where output from the hydrodynamic model is stored on disk and then used to specify advective fluxes for the water quality computations). Storage requirements for long-term hydrodynamic output to drive the water quality model are prohibitive for anything except very small grids. Additionally, reduction in computer time is minimal when hydrodynamic data used to drive water quality are input every timestep.

Autostepping

The model includes a variable timestep algorithm ensuring numerical stability requirements for the hydrodynamics imposed by the solution scheme are not violated.

Restart provision

The user can output results during a simulation that can subsequently be used as input. Execution can then be resumed at that point.

Layer/segment addition and subtraction

The model will adjust surface layer and upstream segment locations for a rising or falling water surface during a simulation.

Multiple inflows and outflows

Provisions are made for inflows and inflow loadings from point/nonpoint sources, branches, and precipitation. Outflows are either specified as releases at a branch's downstream segment or as lateral withdrawals. Although evaporation is not considered an outflow in the strictest sense, it can be included in the water budget.

Selective withdrawal calculations

The model can calculate the vertical extent of the withdrawal zone for a specified flow based on outlet geometry, outflow, and density.

Time-varying boundary conditions

The model accepts a given set of time-varying inputs at the frequency they occur independent of other sets of time-varying inputs.

Outputs

The model allows the user considerable flexibility in the type and frequency of outputs. Output is available for the screen, hard copy, plotting, and restarts. The user can specify what is output, when during the simulation output is to begin, and the output frequency. The present version requires the user to develop output plotting/visualization capabilities. Results for the Panama Lakes study were plotted using in-house codes (profiles) and a combination of third-party software (AGPM and Excel) for time series.

W2 Theoretical Limitations

Hydrodynamics and transport

The governing equations are laterally and layer averaged. Lateral averaging assumes lateral variations in velocities, temperatures, and constituents are negligible. This assumption may be inappropriate for large waterbodies exhibiting significant lateral variations in water quality. While Gatun Lake is a large lake in areal extent and volume, the widths and depths of the branches are similar to those encountered in other W2 applications.

Eddy coefficients are used to model turbulence. The equations are written in the conservative form using the Boussinesq and hydrostatic approximations. Since vertical momentum is not included, the model may give inaccurate results where there is significant vertical acceleration.

Water quality

Water quality interactions are by necessity simplified descriptions of an aquatic ecosystem that is extremely complex. This is one area in which improvements will be made in the future as better means of describing the aquatic ecosystem in mathematical terms and time for incorporating the changes into the model become available. Many of these limitations will be addressed in Version 3.0. The following list describes the major assumptions in the water quality algorithms.

a. *One algal compartment.* The model includes only one algal compartment and thus cannot model algal succession. In particular, temperature dependency for different algal groups and nitrogen fixation for blue-greens is not modeled. Additional algal groups (any number of diatoms, greens, and blue-greens) will be added in Version 3.0

b. *No zooplankton.* The model does not explicitly include zooplankton and their effects on algae or recycling of nutrients.

c. *No macrophytes.* The model does not include the effects of macrophytes on water quality. In many cases, this is a good assumption.

d. *Simplistic sediment oxygen demand.* The model does not have a sediment compartment that models kinetics in the sediment and at the sediment-water interface. This places a limitation on long-term predictive capabilities of the water quality portion of the model. If sediments are modeled, then the model is more predictive; however, sediment oxygen demand is still modeled in a simplistic manner. A fully predictive sediment model that includes carbon diagenesis will be included in Version 3.0.

W2 Numerical Limitations

Solution scheme

The model provides two different numerical transport schemes for temperature and constituents - upwind differencing and the higher-order QUICKEST (Leonard 1979). Upwind differencing introduces numerical diffusion often greater than physical diffusion. The QUICKEST scheme reduces numerical diffusion, but in areas of high gradients generates overshoots and undershoots which may produce small negative concentrations. Elimination of overshoots and undershoots will be included in Version 3.0. In addition, discretization errors are introduced as the finite difference cell dimensions or the timestep increase. This is an important point to keep in mind when evaluating model predictions that are spatially and temporally averaged versus observed data collected at discrete points in time and space.

Computer limits

A considerable effort has been invested in increasing model efficiency. However, the model still places computational and storage burdens on a computer when making long-term simulations. In Version 2.0, most of the computations are now performed using single precision (32 bits) but double precision is still needed for some computations. Year long water quality simulations now typically take less than 10 minutes on a 200 MHZ Pentium Pro.

5 Model Inputs

Gatun Lake Calibration

Period

Selection of a calibration period was complicated by the lack of a consistent data set for all W2 inputs. Ideally, all data required by the model (flow, meteorological, boundary conditions) should come from the same period and be of adequate frequency so that relationships could be determined. This was not the case in this study.

The observed water quality data represented the wet and dry seasons for the years 1972-1974. Therefore, calibration was performed on a synthetic year made up of average wet and dry season conditions for the year 1972-1974. The quasi-calibration obtained for this synthetic period was then applied to calendar year 1972 to assess how well or poorly model performance was when real flow information was used.

Inflows and outflows

Two sets of inflows were used for 1972 calibration. Calibration simulations for the synthetic year consisted of seasonal average flows for the 1972-1974 period for the major tributaries, Table 5-1 and outflows, Table 5-2. Seasonal average values were determined from observed monthly averages for the 1972-1974 period.

Table 5-1
1972-1974 Synthetic Year Inflows (m^3/s)

Tributary	Dry Season	Wet Season
Chagres – Madden Dam Release	65.93	54.31
Rio Gatun	3.03	8.15
Rio Trinidad	2.04	9.30
Rio Ciri Grande	3.51	12.11

Table 5-2 1972-1974 Synthetic Year Outflows (m³/s)		
Withdrawal	**Dry Season**	**Wet Season**
Power Generation	1.76	9.42
Gatun (Atlantic Locks)	44.33	43.19
Pedro Miguel Locks	42.51	40.34
Spillage	13.32	63.20

Daily inflows for the 1972 simulation were obtained from observed data. Fifteen-minute observations for Rio Gatun and Rio Trinidad were processed to generate daily inflows for W2, Figure 5-1. As the Los Canones station on the Rio Ciri Grande was not operational until 1978, no data were available for Rio Ciri Grande inflows. Instead monthly averages for the period of record (1977-2000) were substituted for the Rio Ciri Grande inflow into Lake Gatun. Daily reported discharges from Madden Dam were used to represent headwater inflows.

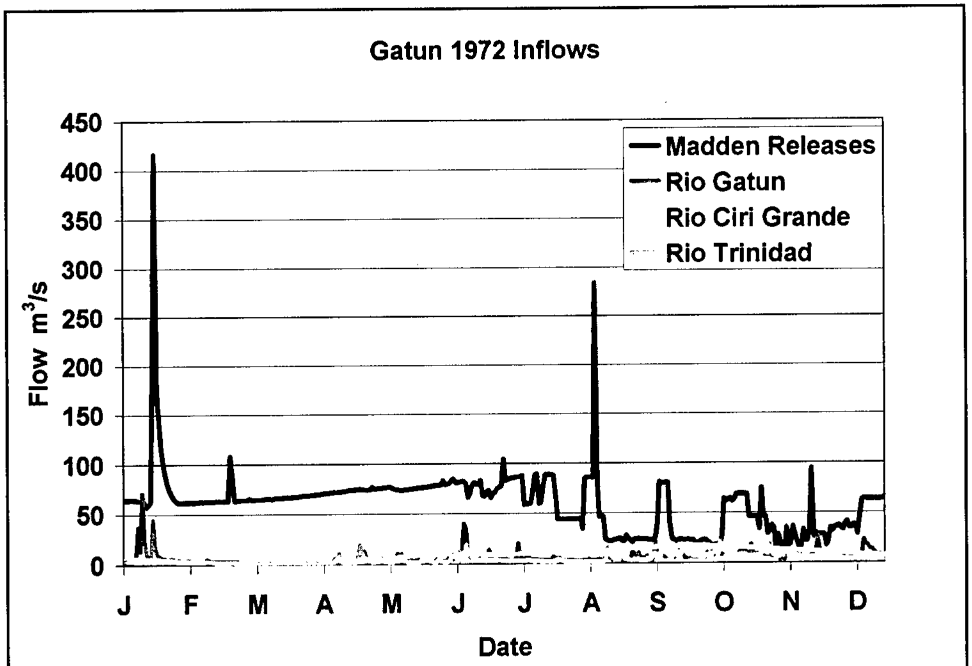

Figure 5-1. Tributary inflows for Lake Gatun calibration

Shown in Figure 5-2 are the reported outflows for the calibration period. Not included are water losses due to evaporation. When comparing the total inflow and the total outflow, it is evident that there is more reported outflow than recorded inflow. This is attributable to the average net rainfall of 1.55 m per year directly to the lake, direct runoff from the watershed, and inflows from minor tributaries. Based upon reported inflows, discharges, rainfall, evaporation, and elevation records the amount of unspecified inflow was calculated, Figure 5-3. This missing flow was input into W2 as a distributed inflow.

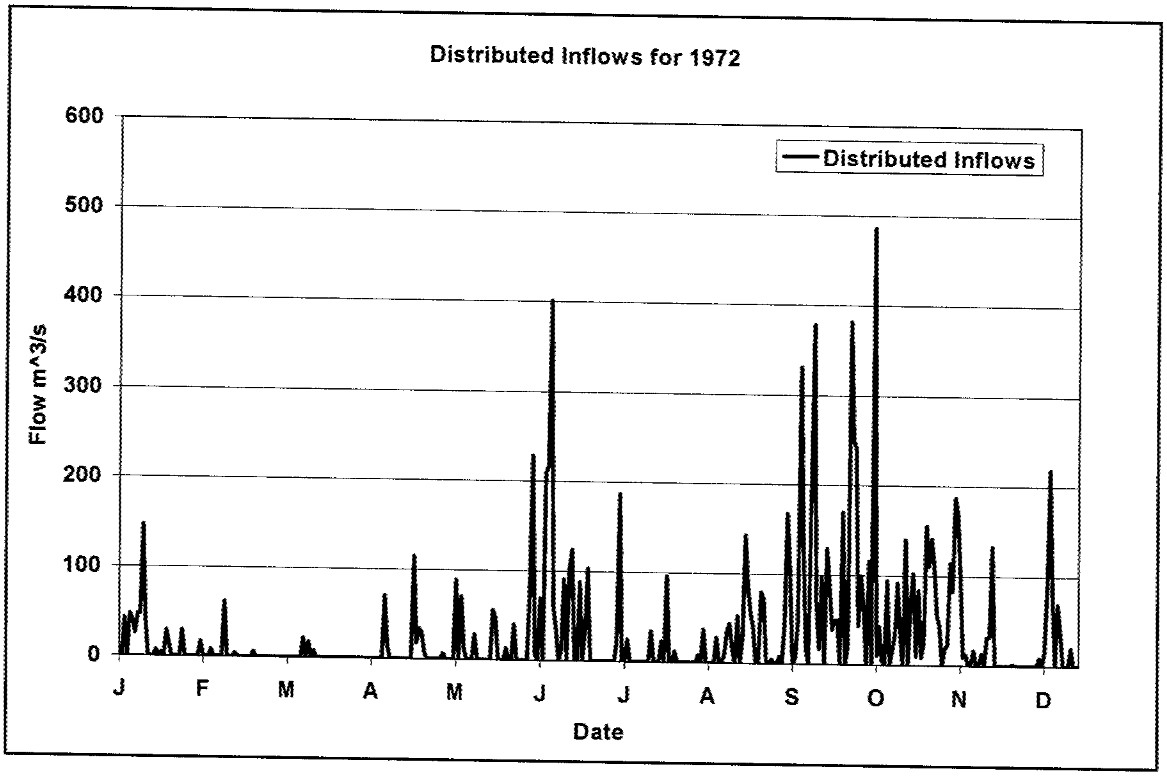

Figure 5-2. Lake Gatun reported outflows

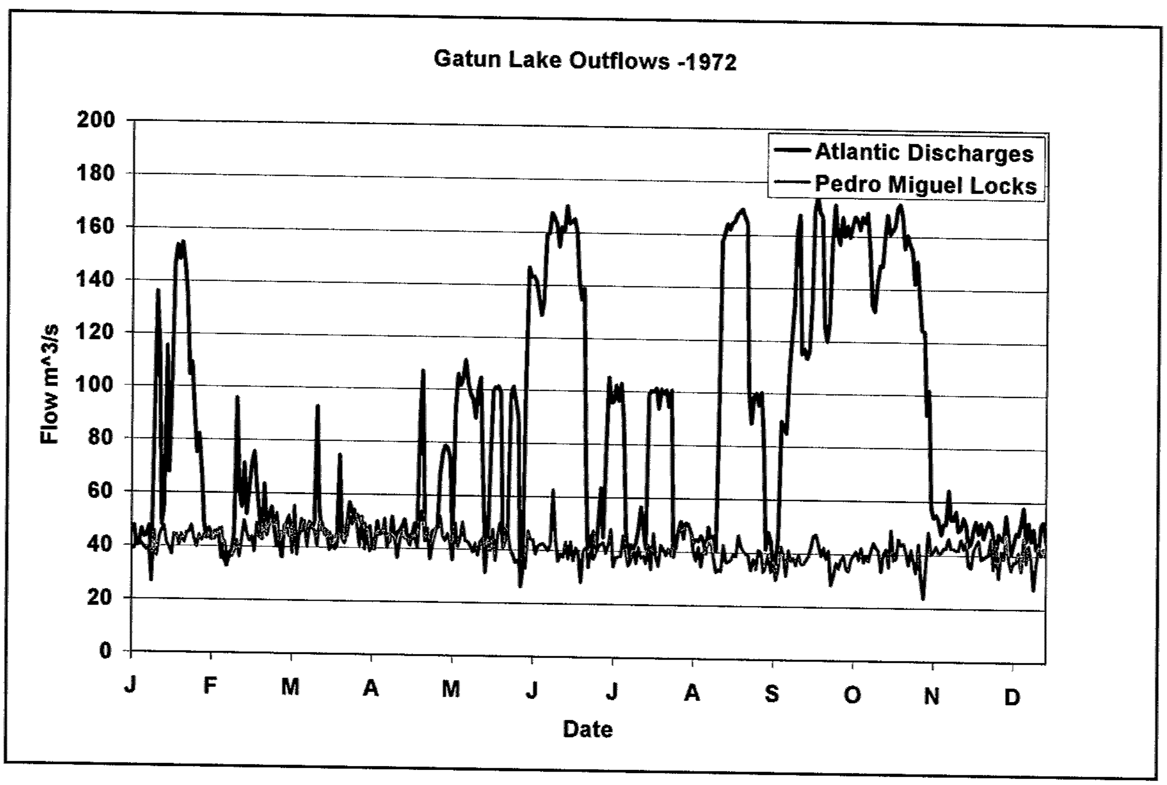

Figure 5-3. Lake Gatun distributed inflows

Meteorological data

Monthly average and extreme air temperature, dew point temperature, wind speed, and wind direction data were available for the period 1985–2000 for meteorological stations at Gamboa and Gatun. Monthly precipitation records for available for the Gatun meteorological station from 1905 to 2000.

Wet season and dry season average air temperature, dew point temperature, wind speed, and wind direction based on the 1985-2000 records were used for the synthetic year simulations, Table 5-3. For the 1972 simulation, monthly averages for the period 1985-2000 were used. Seasonal precipitation rates based upon the observed rainfall at Gatun for the years 1972-1974 were used for the synthetic calibration simulation. For the year 1972 simulation, observed monthly rainfall at Gatun was used.

Table 5-3
1972-1974 Synthetic Year Meteorological Conditions

Parameter	Dry Season	Wet Season
Air Temperature (°C)	26.9	26.6
Dew Point Temperature (°C)	21.0	22.6
Wind Speed (m/s)	2.37	1.43
Wind Direction (Phi Radians)	6.24	5.40

The years 1971 through 1973 were drier than average years for the period of record at Gatun (1905-2000). Total rainfall during those years (101.9 in., 98.5 in., and 90.4 in) were less than the historical average of 117.9 in. If the period since 1970 is considered, these years are still drier than the average (109.4 in.). The year 1974 was a wetter than average year with a total rainfall of 122.6 inches. No temperature or other meteorological data were obtained for the period 1972-1974. However, investigation of the monthly records for the period 1985 to present indicate little variation in the monthly average temperatures over that period. The standard deviation of the monthly average temperatures over that period was less than 1°C for all months except for December, which was 1.2 °C. This indicates that during this period there was little difference in the average air temperature and that monthly or seasonally average temperatures should be representative.

A key piece of data that was missing from the meteorological data for the 1972-1974 period were cloud cover records. Cloud cover is an indirect measure of the amount of sunlight that reaches the water surface. As such, cloud cover impacts temperature predictions and stratification in the water column. Cloud cover values range from 1-10. Lower cloud cover values are indicative of clear skies, higher values correspond to cloudier skies. No cloud cover observations could be located for any of the meteorological stations considered for use. Through trial and error during calibration, a cloud cover of 8 was selected based upon computed water temperature profiles and the degree of stratification exhibited.

Boundary conditions

Listed in Table 5-4 are inflow concentrations for tributaries for Lake Gatun. These values were selected from the results of the 1972-1974 sampling study from the most upstream stations associated with that tributary in the cases of Rio Gatun, Rio Trinidad, or Rio Ciri Grande. For the Rio Chagres, these data are for Station 020 in Lake Madden just above the dam.

Table 5-4
Tributary Boundary Conditions

WQ Const.	Chagres (Madden Dam)		Rio Gatun		Rio Ciri Grande		Rio Trinidad	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
DO (mg/L)	5.0	4.4	6.0	4.4	5.4	6.3	5.0	4.4
PO4 (mg/L)	0.020	0.030	0.094	0.030	0.011	0.020	0.020	0.030
NO3 (mg/L)	0.015	0.097	0.01	0.015	0.01	0.01	0.015	0.097
NH4 (mg/L)	0.07	0.02	0.04	0.03	0.02	0.01	0.07	0.02
BOD (mg/L)	0.90	1.45	0.62	1.25	0.56	0.77	0.9	1.45
Temperature (°C)	28.2	28.15	28.6	28.6	28.2	29.8	28.0	29.2
Fecal Coliform (mpn/100 ml)	1	5	6	1	3	1	1	5

Loading information

Though not technically a point source loading, the Rio Chilibre discharge below Madden Dam was treated as one and included into the model. The Rio Chillibre exhibited degraded water quality conditions in the 1970s. Flows for the Rio Chilibre were scaled from Rio Gatun records and included in the model. Observations from station 110 were used for influent conditions. Flow and concentration information for all point source loads are listed in Table 5-5.

Table 5-5
Significant Loads to Lake Gatun

	Gamboa Outfall		USNS Summit		Rio Chilibre	
	Dry	Wet	Dry	Wet	Dry	Wet
DO (mg/L)	2.0	2.0	2.0	2.0	2.8	2.7
PO4 (mg/L)	11.0	12.1	4.4	4.4	0.038	0.075
NO3 (mg/L)	13.6	23.6	0.05	0.05	0.023	0.22
NH4 (mg/L)	0.059	0.073	9.0	9.0	0.04	0.03
BOD (mg/L)	149	149	126	126	0.33	0.67
Temperature (°C)	28.2	28.2	28.15	28.2	28.2	28.15
Fecal Coliform (mpn/100 mL)	10000	100000	10000	10000	50	1064
Q (m^3/s)	0.01	0.01	0.001	0.001	2.8	7.8

Bathymetry

The primary sources used to generate the bathymetry for Lake Gatun were a NIMA chart entitled "Republic of Panama" 1997 edition and NIMA chart entitled "The Panama Canal from Gatun to Gamboa".

Shown in Figure 5-4 is the W2 segmentation of Gatun Lake. The transfer tunnel discharge site is shown in red while the locations of the M&I water intakes are shown in blue. There are a total of 8 branches with the majority of the reservoir being represented by Branches 1 and 4. The canal route lies in Branch 1 and 8. There are a total of 2245 cells in the grid.

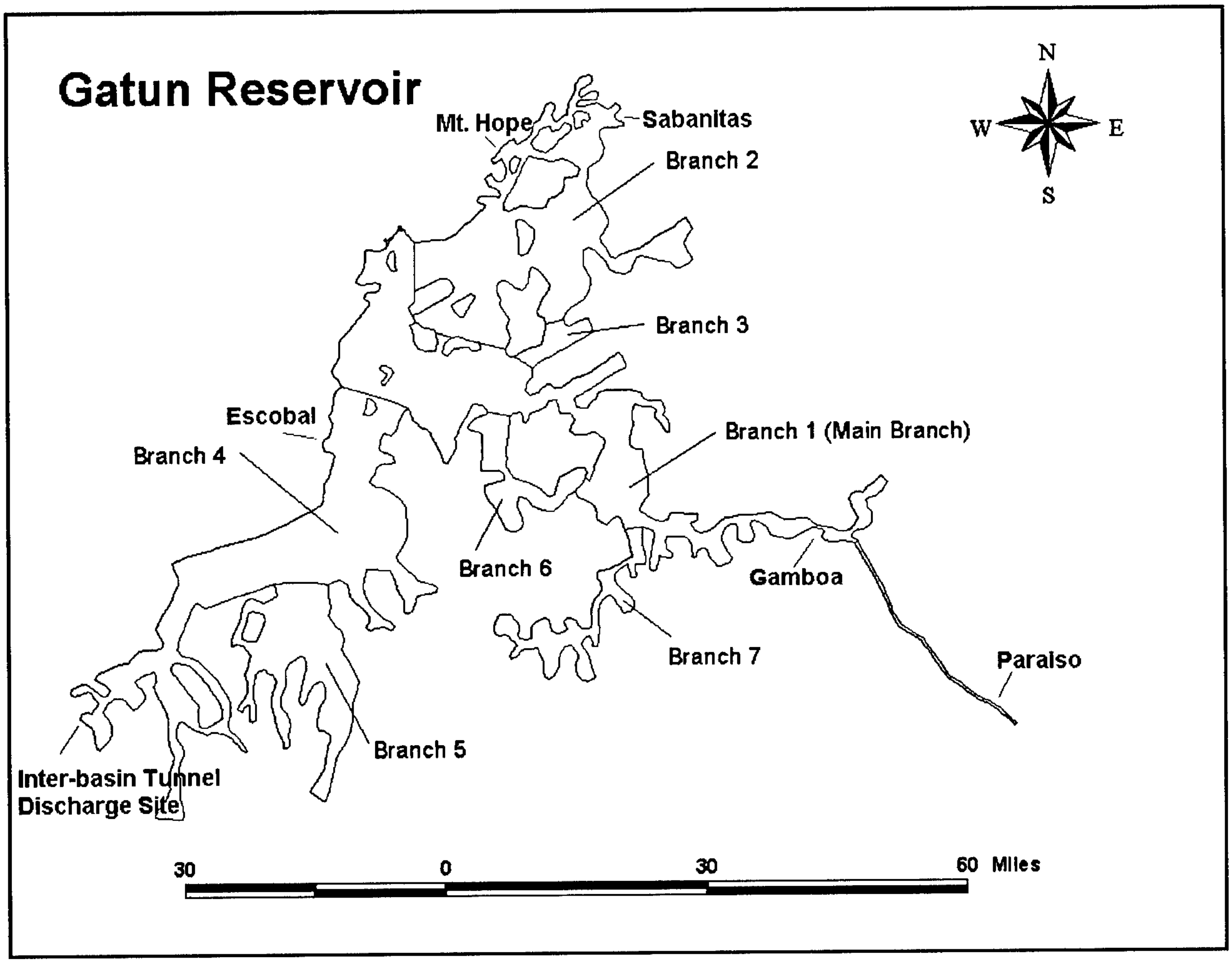

Figure 5-4. Lake Gatun segmentation

Madden Lake Calibration

Period

As was the case with the Gatun Reservoir, selection of a calibration period was complicated by the lack of a comprehensive data set for all W2 inputs. After careful review of the flow and meteorological data sets, the 1988 calendar year was selected as the calibration data set.

Inflows and outflows

There were four flow data sets, Figure 5.5, used as boundary conditions within the model. The Chico, Candelaria, and Peluca, inflows were taken from the observed data sets. The inflows labeled "Khalid Inflows," were flows resulting from watershed analyses that were not accounted for in the major stream inflows. The outflows used for this study were observed flows measured at the Madden Lake Dam.

Meteorological data

Daily meteorological data was used in the modeling of Madden Lake, except for the Wind Direction data set, Figures 5.6-5.8. The daily values of wind direction were not available, so monthly average values were used, Figure 5.9. Monthly average precipitation, from the Gamboa gage, Figure 5.10, was used to estimate loadings due to rainfall.

Boundary conditions

The Chico inflows were applied at the upstream of Branch 1. The Candelaria inflows were applied at the upstream end of Branch 2. The Peluca inflows were applied at the upstream of Branch 4. The minor inflows were applied at the upstream end of Branch 5. Branch 3 did not have any inflows applied to it. The Madden Dam outflows were applied at the downstream of Branch 1. Precipitation was applied uniformly over all segments within the model.

Loading information

Loading information, Tables 5.6-5.9, were average values estimated from observed measurements taken in the 1970s. These average values were applied based upon wet season, May through December, and dry season, January through April.

Bathymetry

The primary sources used to generate bathymetry for Madden Lake were a NIMA chart and sediment range measurements.

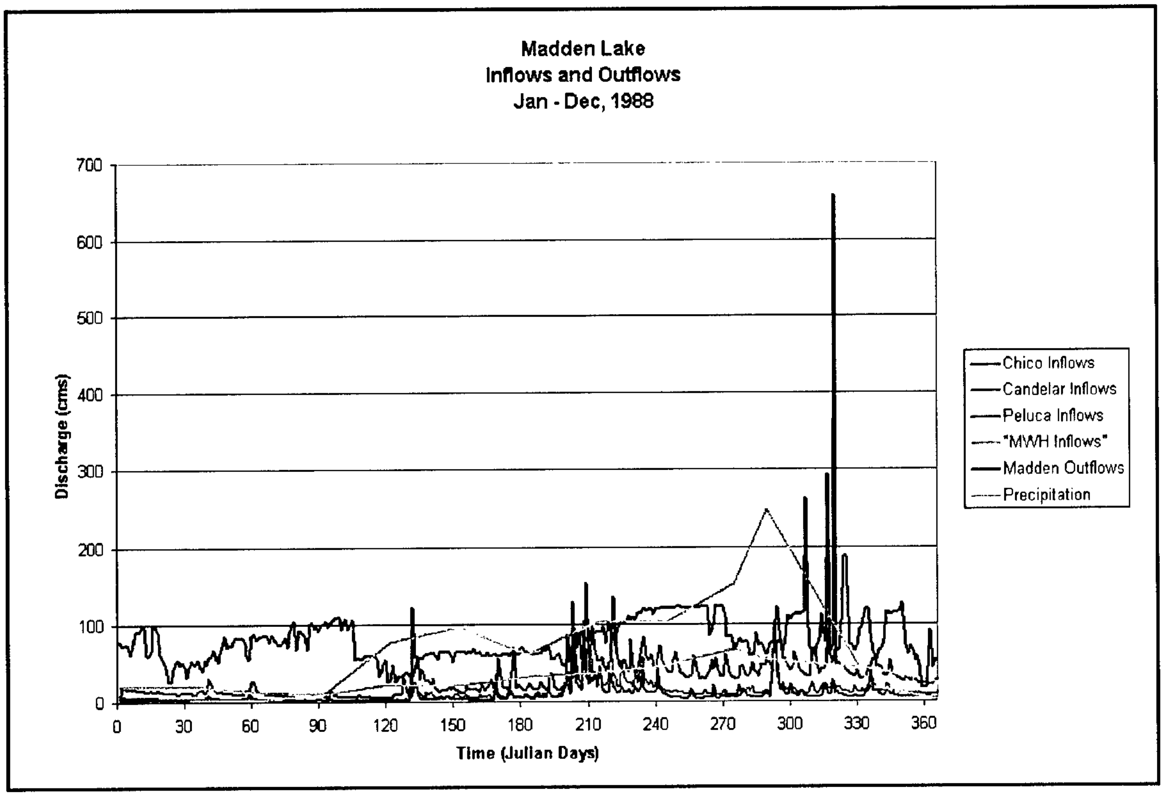

Figure 5-5. Madden Lake inflows and outflows

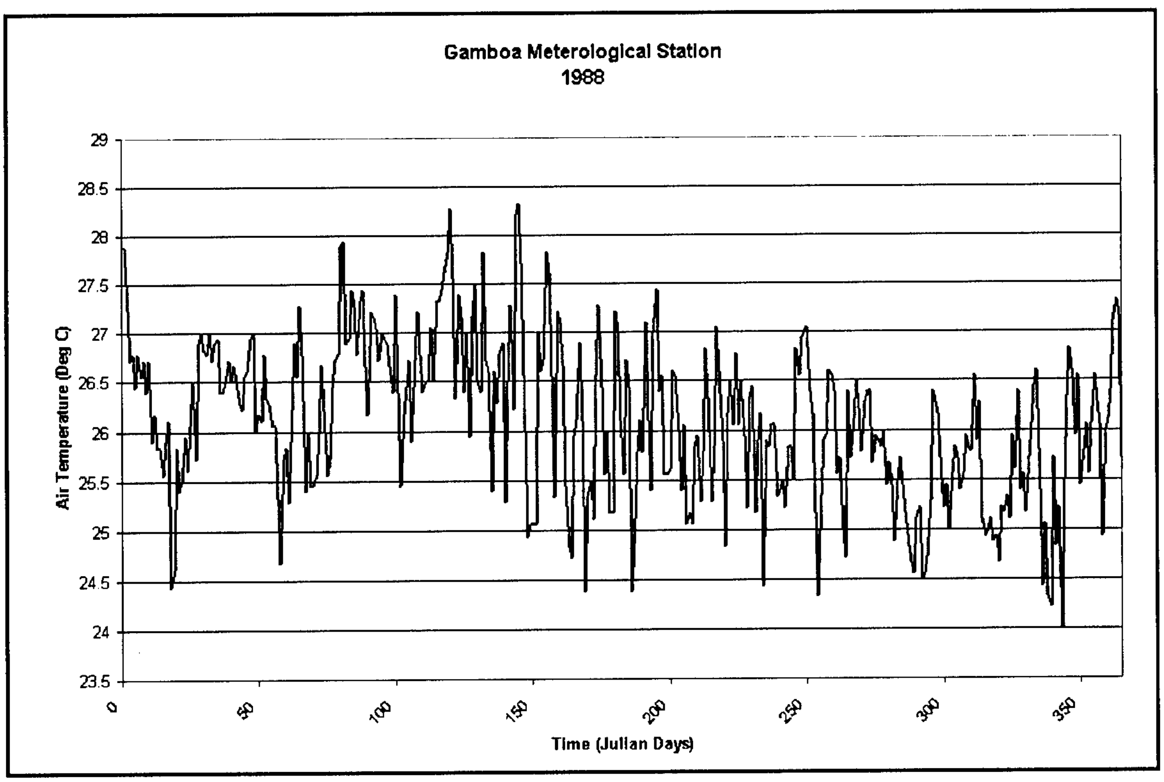

Figure 5-6. Gamboa air temperatures (deg C)

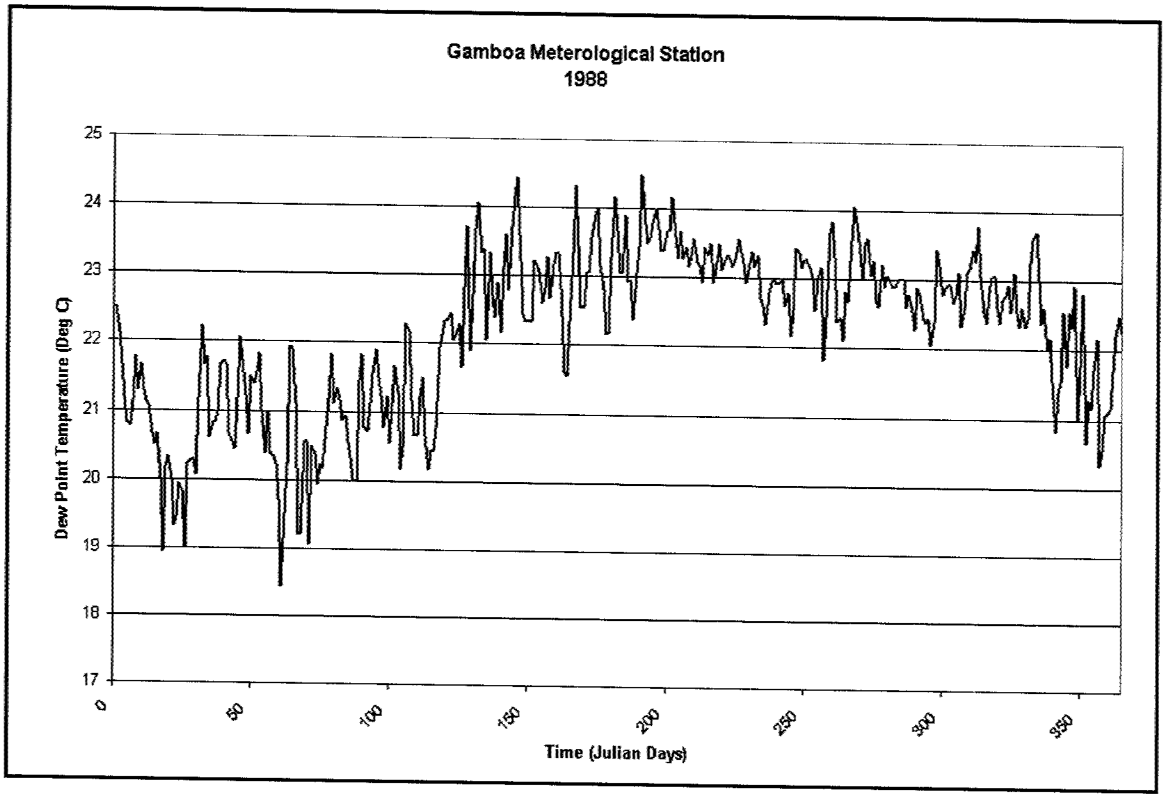

Figure 5-7. Gamboa dew point temperatures (deg C)

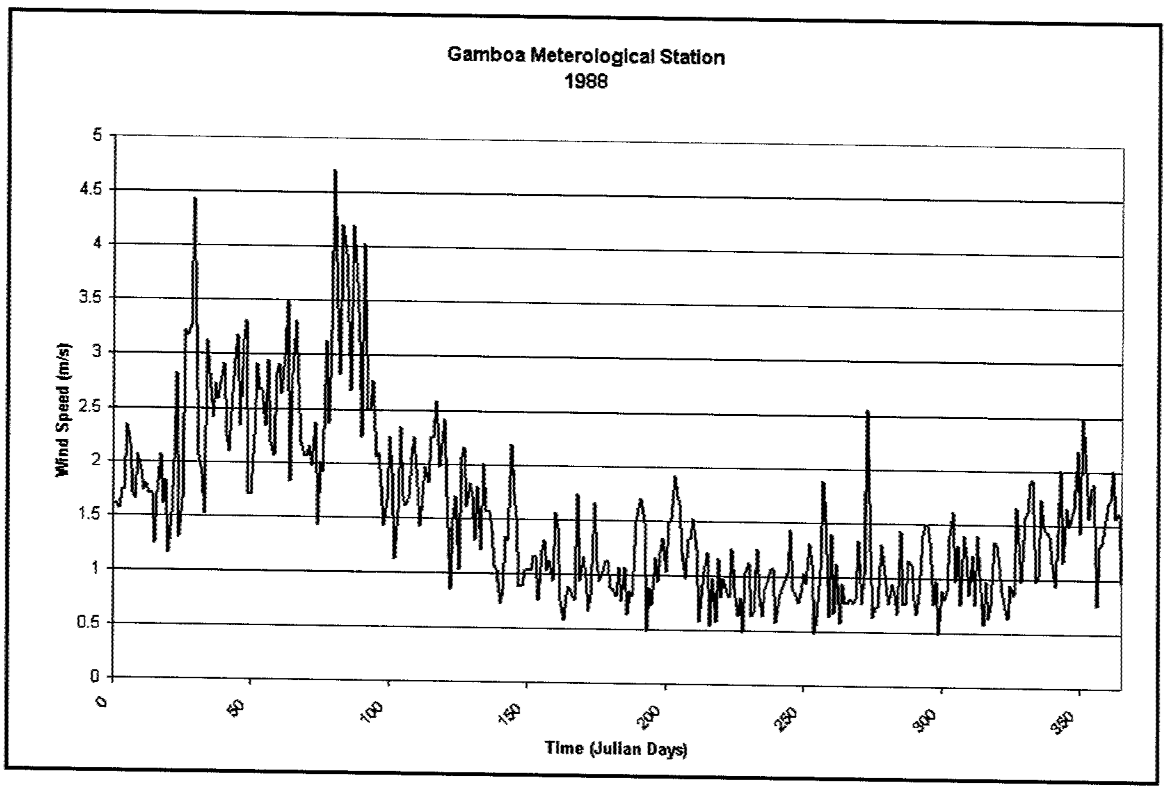

Figure 5-8. Gamboa wind speed (m/s)

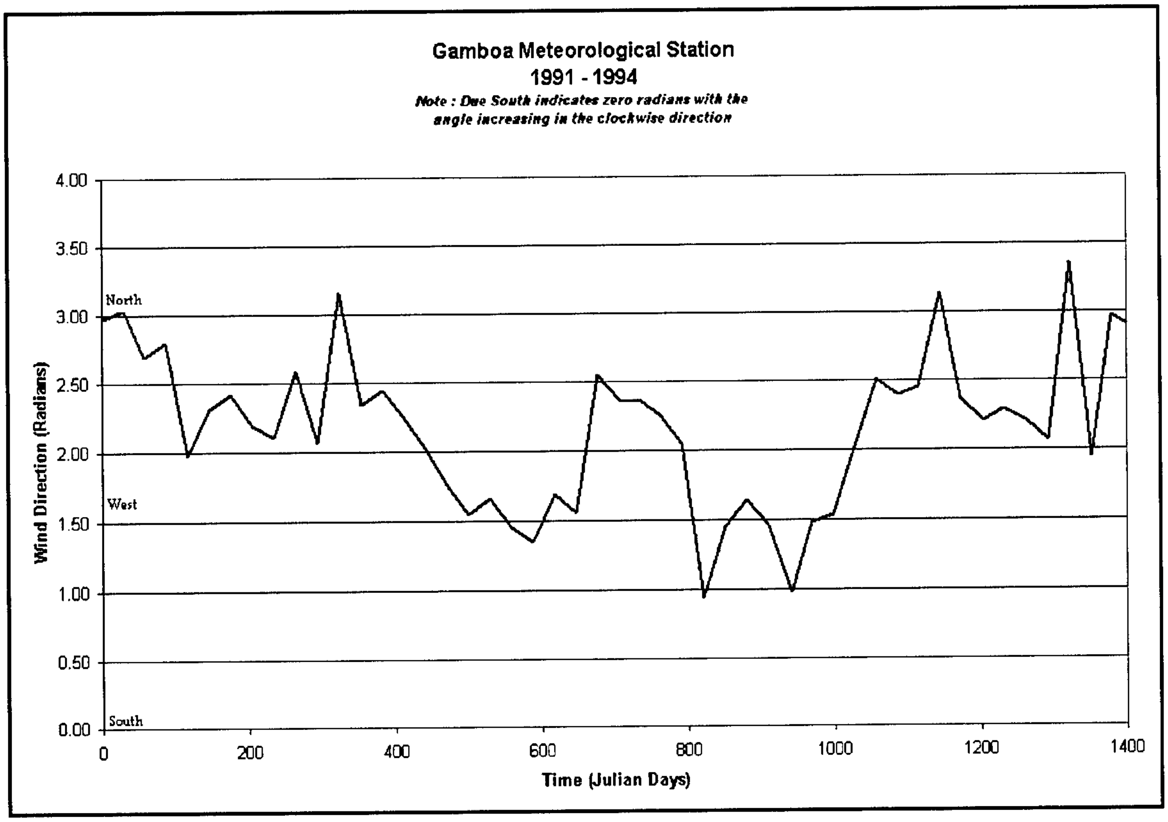

Figure 5-9. Gamboa wind direction (radians)

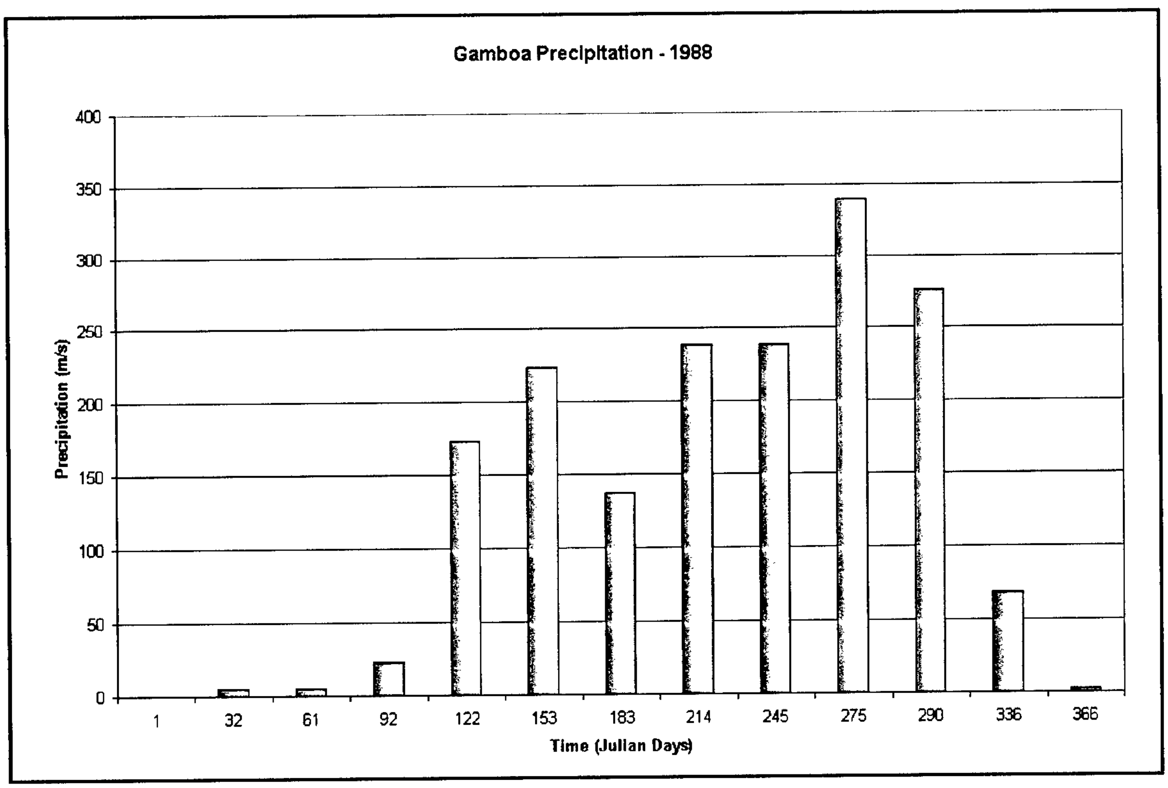

Figure 5-10. Gamboa precipitation (mm)

Table 5-6
Madden Lake Tributary Constituent Concentrations - Chico

Julian Day	ISS	CLFORM	PO4	NH4	NO3	O2	CBOD
0	102.0	18.0	0.050	0.130	0.015	6.850	2.660
121	102.0	18.0	0.050	0.130	0.015	6.850	2.660
122	102.0	18.0	0.035	0.020	0.015	7.200	1.300
335	102.0	18.0	0.035	0.020	0.015	7.200	1.300
336	102.0	18.0	0.050	0.130	0.015	6.850	2.660
366	102.0	18.0	0.050	0.130	0.015	6.850	2.660

Table 5-7
Madden Lake Tributary Constituent Concentrations - Peluca

Julian Day	ISS	CLFORM	PO4	NH4	NO3	O2	CBOD
0	108.0	1.5	0.024	0.030	0.010	6.000	0.760
121	108.0	1.5	0.024	0.030	0.010	6.000	0.760
122	108.0	88.0	0.031	0.030	0.014	7.400	0.760
335	108.0	88.0	0.031	0.030	0.014	7.400	0.760
336	108.0	1.5	0.024	0.030	0.010	6.000	0.760
366	108.0	1.5	0.024	0.030	0.010	6.000	0.760

Table 5-8
Madden Lake Tributary Constituent Concentrations - Candelaria

Julian Day	ISS	CLFORM	PO4	NH4	NO3	O2	CBOD
0	108.0	1.5	0.024	0.030	0.010	6.000	0.760
121	108.0	1.5	0.024	0.030	0.010	6.000	0.760
122	108.0	88.0	0.031	0.030	0.014	7.400	0.760
335	108.0	88.0	0.031	0.030	0.014	7.400	0.760
336	108.0	1.5	0.024	0.030	0.010	6.000	0.760
366	108.0	1.5	0.024	0.030	0.010	6.000	0.760

Table 5-9
Madden Lake Tributary Constituent Concentrations – Khalid's Flows

Julian Day	ISS	CLFORM	PO4	NH4	NO3	O2	CBOD
0	108.0	1.5	0.024	0.030	0.010	6.000	0.760
121	108.0	1.5	0.024	0.030	0.010	6.000	0.760
122	108.0	88.0	0.031	0.030	0.014	7.400	0.760
335	108.0	88.0	0.031	0.030	0.014	7.400	0.760
336	108.0	1.5	0.024	0.030	0.010	6.000	0.760
366	108.0	1.5	0.024	0.030	0.010	6.000	0.760

6 Model Calibration

Gatun Lake

Two "periods" were chosen for calibrating W2 for Gatun Lake. As the available water quality data were summaries for the years 1972-1974, one calibration period was a syntheic year composed of the seasonal average flow conditions for the years 1972, 1973, and 1974. The other calibration period was the calendar year 1972. The fundamental differences between these two simulations were the tributary input data origin and frequency. Meteorological conditions for the 1972 simulation were monthly averages while seasonally averaged meteorological data was used for the synthetic year simulation. Seasonal averaged precipitation rates for 1972-1974 were used for the synthetic year while observed monthly precipitation rates from 1972 were used for the 1972 simulation.

A limited suite of variables were modeled based upon data availability and relevance. Temperature, dissolved oxygen, nitrate, ammonia, phosphorus, fecal coliform, and CBOD were simulated. A conservative tracer was also simulated in place of suspended solids as that data was unavailable for boundary conditions.

Shown in Figure 6-1 are stations where W2 mid–depth time series results for the synthetic year were compared to the observed data summary in Figure 6-2 through Figure 6-33. Figures 6-34 through 6-65 contain comparisons of mid-depth model output for the year 1972 and the observed data summary.

Shown in Figure 6-66 are locations where W2 profile results were compared to observed data summaries for the synthetic year and 1972 calibration simulations. Figures 6-67 through 6-82 are the profile results for the synthetic year while Figure 6-83 through 6-98 are for 1972.

Synthetic year (average conditions) simulation time series

Time series results, Figure 6-2 – 6-33 indicate that W2 is performing adequately. Coliform predictions, Figures 6-2, 6-10, 6-18, and 6-26, indicate that the model is doing a good job simulating coliform. The model predictions are high for the summer in segments 12 and 15 possibly as a result of the Gamboa point source load. Loads for coliforms were not reported and had to be estimated based upon instream conditions. The observed values at these locations are low, near detection limits, that slight model over predictions are not significant. Tracer time series results, Figures 6-3, 6-11, 6-19, and 6-27, demonstrate the flushing of the

Gatun Lake over time. The waters of Gatun Lake have an initial concentration of 1 mg/L of tracer. No additional tracer is added during the simulation.

Time series for ammonium, Figures 6-4, 6-12, 6-20, and 6-28, indicate that W2 is under- predicting observed values. Ammonia levels in Gatun Lake are low except in location near settlements where there may be un-regulated sewage discharges. Model predictions in comparison to observed values that are at or below detection limits must be viewed with the understanding that the model can compute levels lower than detection level. Another source of ammonia is from sediment releases which occur under anoxic conditions. There is evidence in these plots and animations that such release occur in the model. However, the magnitude of such releases is not sufficient to bring model predictions up. Time series predictions for Phosphorus indicate that the model is performing well, Figures 6-5, 6-13, 6-21, and 6-29.

Time series results for Dissolved Oxygen indicate that the model is performing well, Figures 6-6, 6-14, 6-18, and 6-30. Model predictions are higher than the observed ranges, but considering that the model output represents a specific depth and the observed data is a summary, model performance for dissolved oxygen is considered good. Time series results for Nitrite-Nitrate indicate that the model is overpredicting, Figures 6-7, 6-15, 6-23 and 6-31. It is possible that this is the results of excessive nitrification of ammonia, however a very low nitrification rate was used.

W2 temperature predictions are shown in Figures 6-8, 6-16, 6-24, and 6-32. Overall the model is doing an adequate job of predicting temperature. The model slightly underpredicts the range of observed temperature in segment 12, Figure 6-8, during the wet season. Performance at the other three stations is better. Considering the temporal and spatial variability of water temperature, influence of external flows, and the average nature of the data and the meteorological data used in this study, model performance for temperature is considered good. CBOD time series results are likewise good although the model does tend to be lower than observed values, Figures 6-9 6-17, 6-25, and 6-33.

1972 calibration time series

Time series results for the simulation made using 1972 calendar year flows are very similar to those of the simulation made with the synthetic year inflows. This was expected and served to demonstrate the robustness of the mode configuration. Results for the 1972 calibration year indicated more variability as a result of the changing inflows and resulting loads.

Coliform results, Figures 6-34, 6-42, 6-50, and 6-58, demonstrate greater variability and higher peak concentrations than the observed data summary maximum. That the model exceeds the observed data summary maximum vale is not of great concern as the observed data summary maximum represents a single observation and is not part of a continuous record. Tracer results, Figures 6-35, 6-43, 6-51, and 6-59 show the same shapes as the plots from the synthetic year. Ammonia results, Figures 6-36, 6-44, 6-52, and 6-60, are likewise similar to those of the synthetic year. Phosphorus results, Figures 6-37, 6-45, 6-53, and 6-61, indicate slightly higher levels and greater variability but are still good.

Dissolved oxygen results, Figures 6-38, 6-46, 6-54, and 6-62, are similar to those of the synthetic year. The use of the 1972 calendar year flows exaggerated the results of the synthetic year simulations with over-predictions of DO getting higher. However, model performance is still considered to be good. Nitrate results, Figures 6-39, 6-47, 6-55, and 6-63 are similar to those of the synthetic year as are Temperature, Figures 6-40, 6-48, 6-56, and 6-64. CBOD results, Figures 6-41, 6-49, 6-57, and 6-65, showed more variability as was expected due to the nature of the variable inflows and loadings.

Overall, the time series results of the 1972 calibration are very similar to those of the synthetic year calibration. Model performance is considered to be good considering the lack of data and the simplistic modeling approach.

Profile plots

Profile plots for the synthetic year calibrations, Figures 6-67 – 6-82, and the 1972 calibration, Figures 6-83 – 6-98, indicate model performance at 11 stations on two dates. The dates, April 29 and Nov 30, were arbitrarily selected. Some insight is gained from the profile plots that are not available from the time series plots.

Model results are plotted as dotted lines and observed seasonal averages in that W2 segment are plotted as an "x". In the event that there were maxima and minima they are also plotted as "x" which results in there being two or three "x" on the graph. Instances where model predictions pass through the middle "x" are indicative of model agreement with the reported average for that segment. Unless otherwise indicated in (CCP, 1975) all observed data values were plotted at mid-depth.

Profile plots for the conservative tracer, Figures 6-67, 6-75, 6-83, 6-91, and temperature, figures 6-74, 6-82, 6-90, 6-98, indicate that there is little thermal stratification in the model. This agrees with (PCC 1975) which states that the maximum temperature variation observed was 0.4 °C. The temperature profiles were also used to determine an appropriate value for cloud cover. Use of lower cloud cover values, 7 and below, which represented sunnier conditions resulted in excessive heating and temperature rise in the surface layers. Use of higher cloud cover values, 9-10, representing cloudier conditions resulted in lower temperatures throughout the water column.

Dissolved oxygen profiles, Figures 6-72, 6-80, 6-88, 6-96, indicate that there is some levels of dissolved oxygen stratification. For most segments, it is impossible to determine whether there is truly stratification as only mid-depth values are available. For segments 43, 46, and 47 there are surface and bottom observations of DO and the model does predict within the ranges of the observations. Model results indicate lower bottom DO levels in segments 16,18, 19, and 50 in the 1972 calibration run than in the synthetic year simulation. DO levels fell off near the bottom of the water column indicating that it might be related to SOD. SOD rates throughout the system were specified as 0.1 g/m^2 –day with the exception of Branch 4 where SOD rates were set to 0.2 g/m^2 –day. The higher rate was specified in Branch 4 to account for tributary loads from the Rio Ciri Grande and Rio Trinidad. Data from segments in this branch indicated that bottom DO levels were lower than surface. Trial runs using higher SOD rates resulted in excessive anoxia and releases of ammonia.

Profile plots for Phosphorus, Figures 6-69, 6-77, 6-85, 6-93, Ammonia, Figures 6-70, 6-78, 6-86, 6-94, and Nitrate-Nitrite, Figures 6-71, 6-79, 6-87, 6-95, indicate little vertical variation. Phosphorus is uniform throughout the water column in most instances while ammonia levels were low throughout the water column. Nitrate did decrease near the bottom in segments that also had low DO levels which is indicative of denitrification occurring at these locations. CBOD, Figures 6-73, 6-81, 6-89, 6-97, showed little variation with depth at all locations except for segment 4 which is heavily influenced by flows from Madden Dam, the Rio Chilibro, and the loading of the Gamboa outfall. Coliform levels, Figures 6-67, 6-75, 6-83, 6-91, indicated some variation but were relatively uniform except for locations in close proximity to significant sources.

Overall, the profile plots are a further indication of acceptable model performance. The model is generally within the range of the observations.

Model performance is felt to be adequate for the task required considering the lack of a synoptic data set with which to calibrate the model.

Water surface elevation

A final indication of model performance is shown in Figure 6-99, which is the water surface elevation time series for the 1972 calibration. As is indicated, W2 replicated the recorded water surface elevation with an acceptable degree of accuracy. The difference between the computed and 1972 calibration water surface levels result from different levels of evaporation in the two simulations. The computed simulation was made with a cloud cover of 5 while the 1972 calibration was performed with a cloud cover of 8. The additional cloud cover decreased the computed evaporation during the simulation which resulted in slightly higher water surface elevations.

Madden Lake

The calibration period chosen for this study was calendar year 1988. This year was picked based upon a data evaluation which indicated that there was sufficient water quantity and water quality data with which to perform the calibration. Model versus observed comparisons were made at MAD-020, MAD-060, MAD-070, and MAD-120, Figure 6-100. The model time series results were taken at an average depth, at each observation site location, in order to compare the model results to the observed maxima, minima, and average water quality constituents.

From Figures 6-101, 6-109, 6-117, and 6-125, the model seemed to simulate the average water temperature relatively well throughout the model during the wet season. During the dry season, the model performed well towards the upper portion of the lake, however, in other locations, the results were not as good. From Figures 6-102, 6-110, 6-118, and 6-126, the model seemed to be consistently low in estimating the CBOD throughout the system. From Figures 6-103, 6-111, 6-119, and 6-127, did a relatively good job of estimating the dissolved oxygen for both the dry season as well as the wet season. From Figures 6-104, 6-112, 6-120, and 6-128, was able to simulate nitrate-nitrite relatively well during the wet season throughout the model, however, during the dry season, the model was not able to estimate the concentrations as well. From Figures 6-105, 6-113, 6-121, and 6-129, the model continued to simulate the ammonia well during the wet season, however, the model was not able to simulate the ammonia very well during the dry season. From Figures 6-106, 6-114, 6-122, and 6-130, the model seemed to do a good job of simulating phosphorus both in the wet season as well as the dry season throughout the system. From Figures 6-107, 6-115, 6-123, and 6-131, the coliform count seems to be too low in the lower portion of the lake while the model did a good job of simulating the coliform count in the upper portions of the lake during the wet season. From Figures 6-108, 6-116, 6-124, and 6-132, the model did a good job of simulating the total solids for the wet season throughout the system. There was not dry season data for total solids, so the model could not be calibrated for that time period.

Overall, the model seemed to do very well in simulating all constituents during the wet season throughout the system. The model was not able to simulate as well in the dry season. As more measured data is collected, then the model can continue to be calibrated to better simulate during the dry season. Also, the model was calibrated to average, maxima, and minima conditions. As more time varying water quality data is collected, then better model performance can be gained from further calibration.

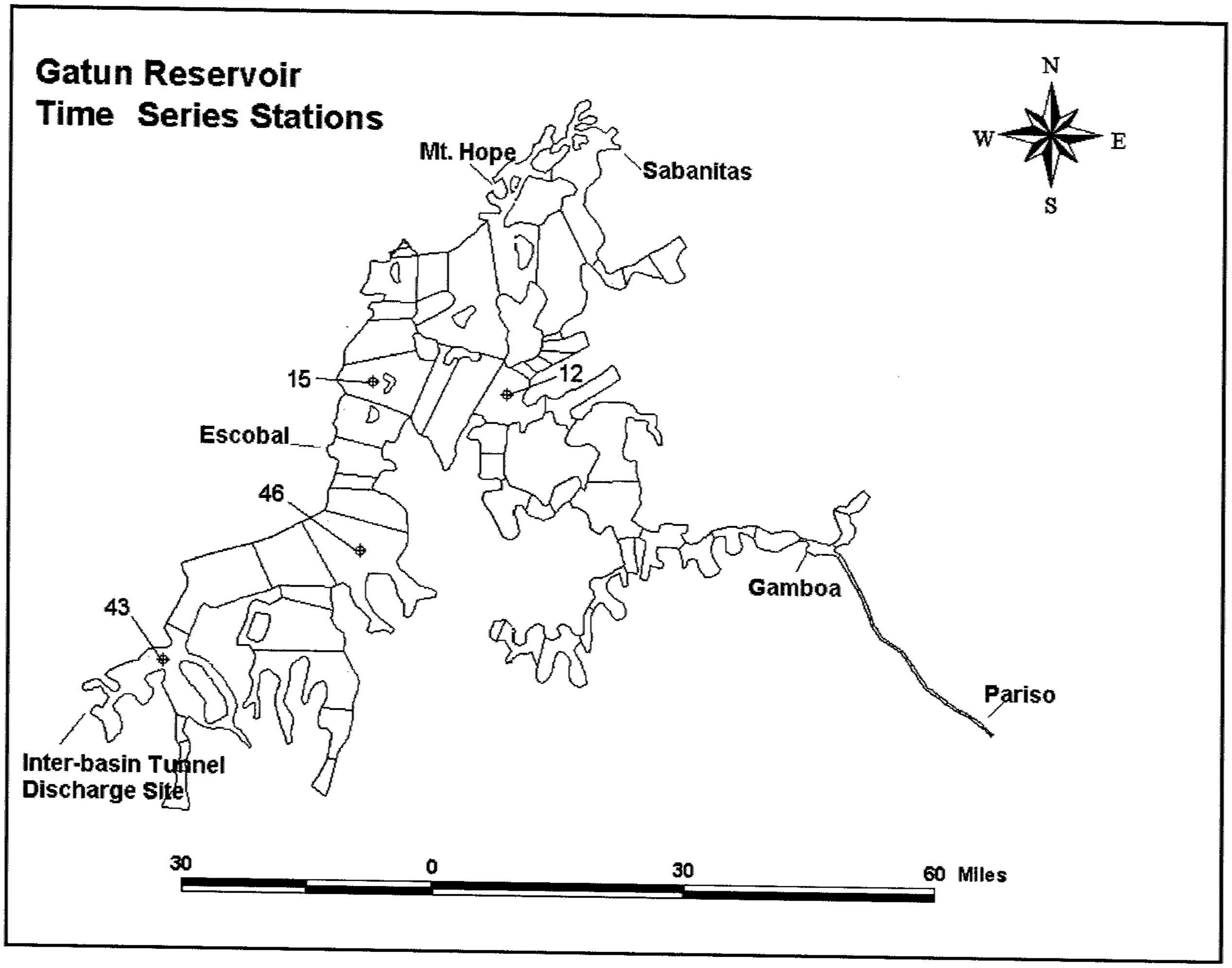

Figure 6-1. Gatun Lake segments used for time series comparisons

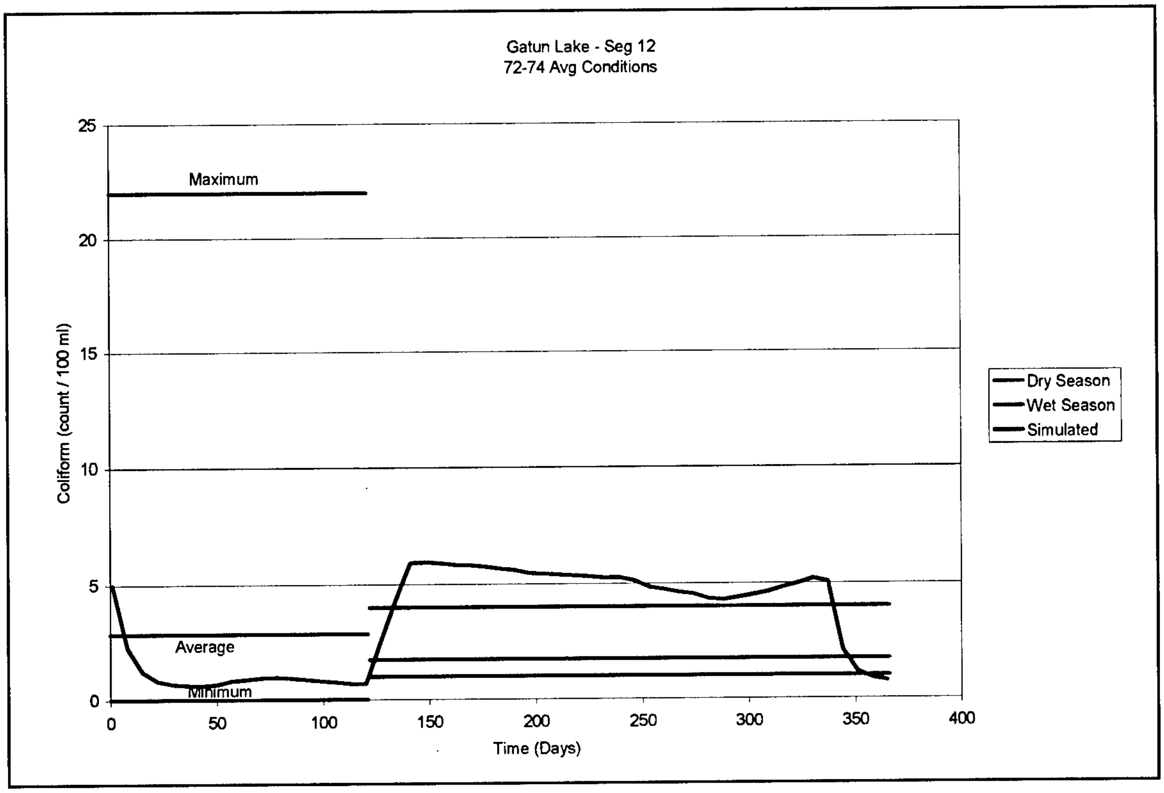

Figure 6-2. Average conditions calibration coliform, segment 12

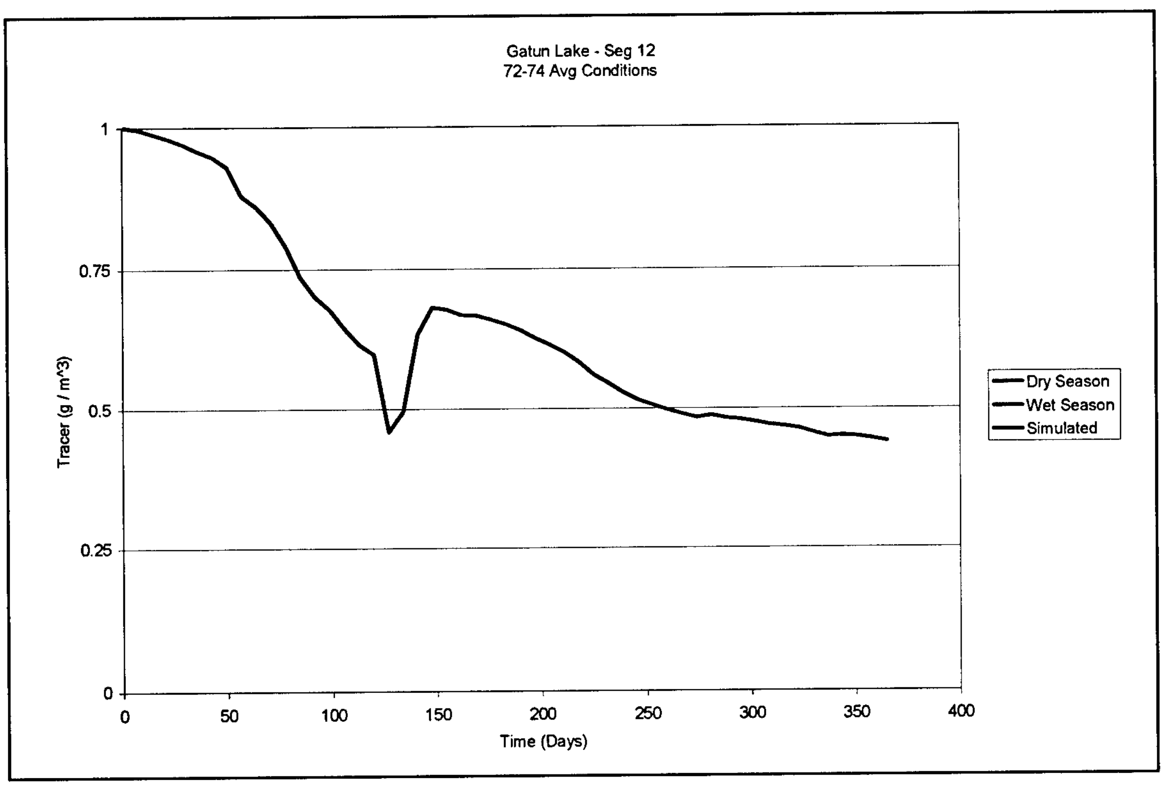

Figure 6-3. Average conditions calibration tracer, segment 12

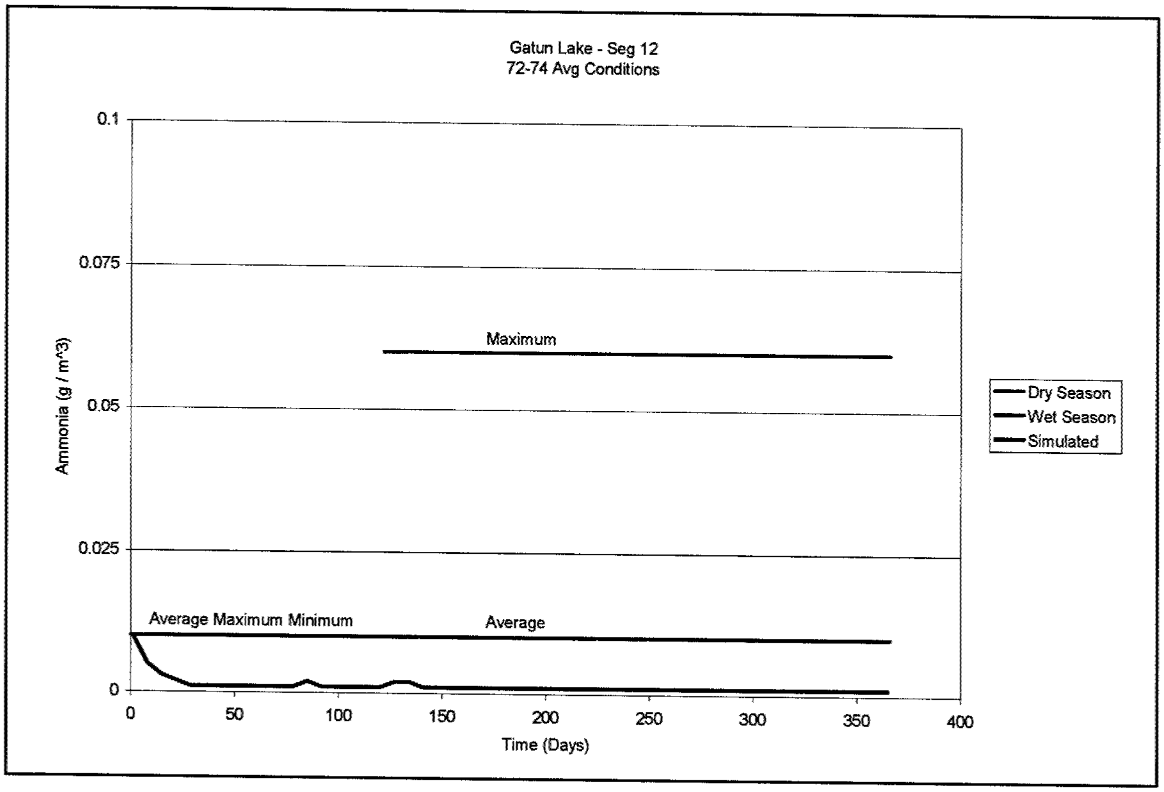

Figure 6-4. Average conditions calibration ammonia, segment 12

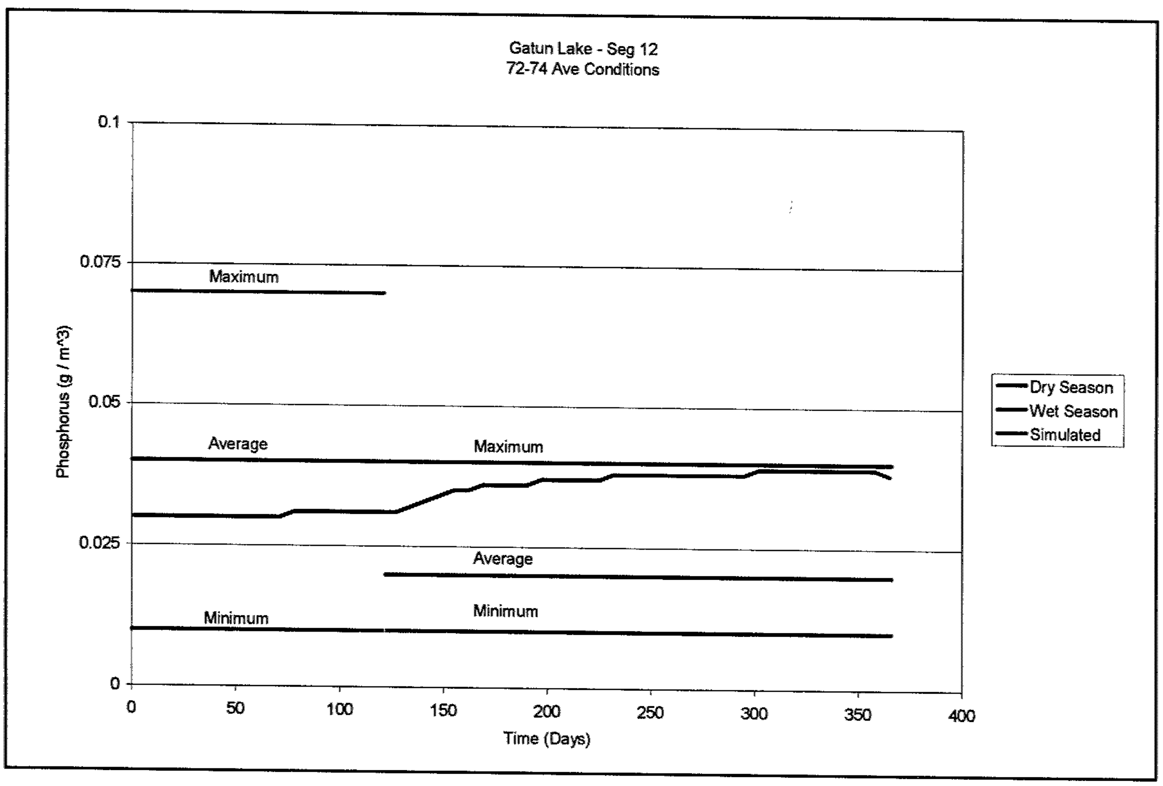

Figure 6-5. Average conditions calibration phosphorus, segment 12

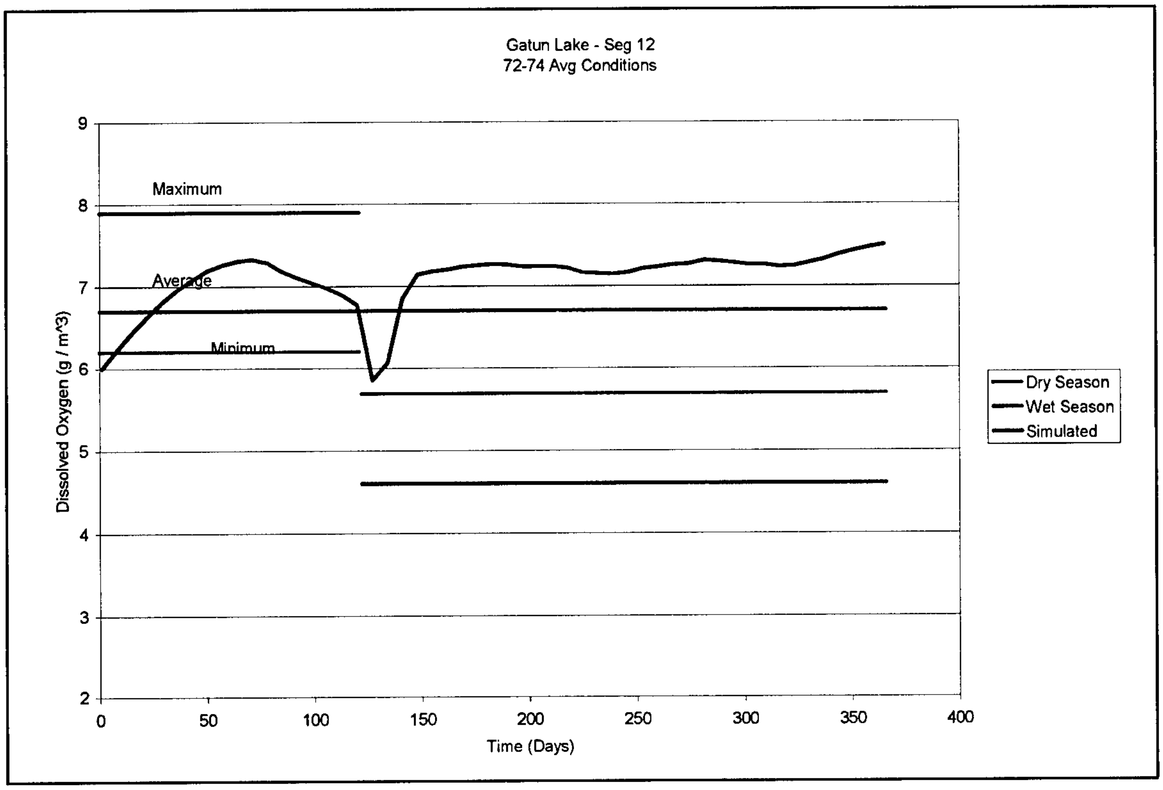

Figure 6-6. Average conditions calibration dissolved oxygen, segment 12

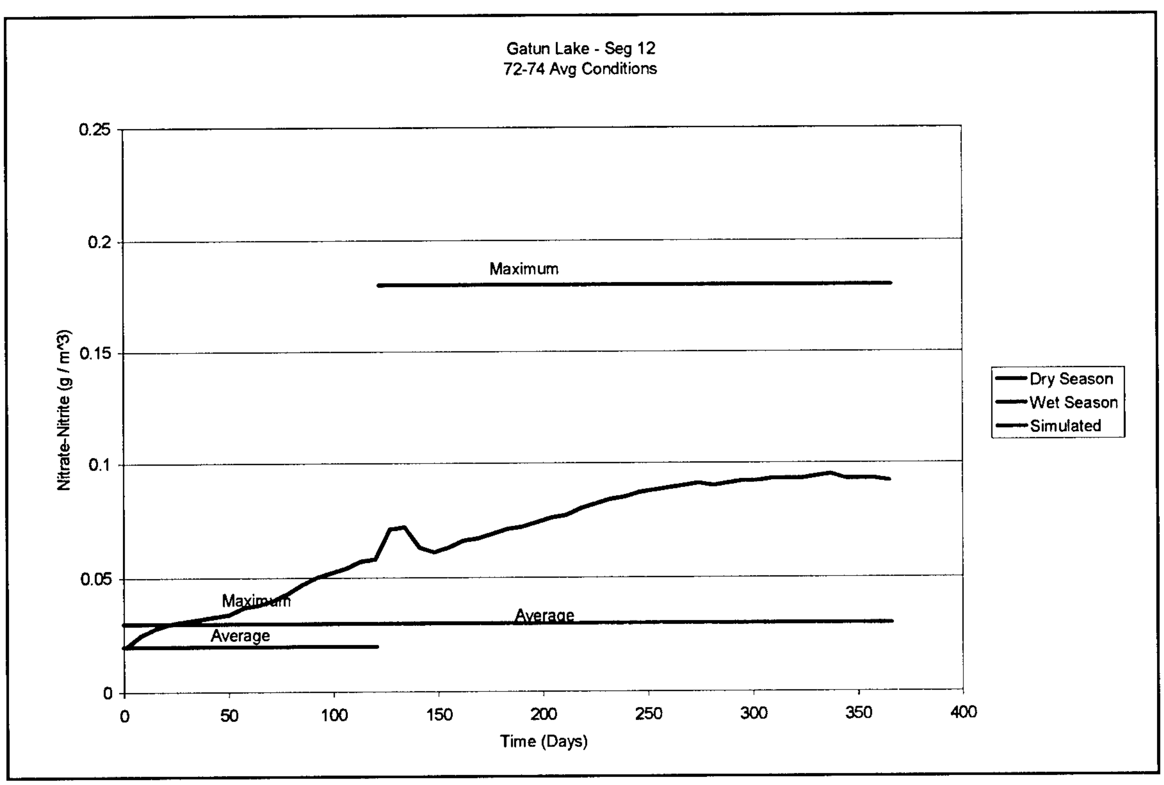

Figure 6-7. Average conditions calibration nitrite-nitrate, segment 12

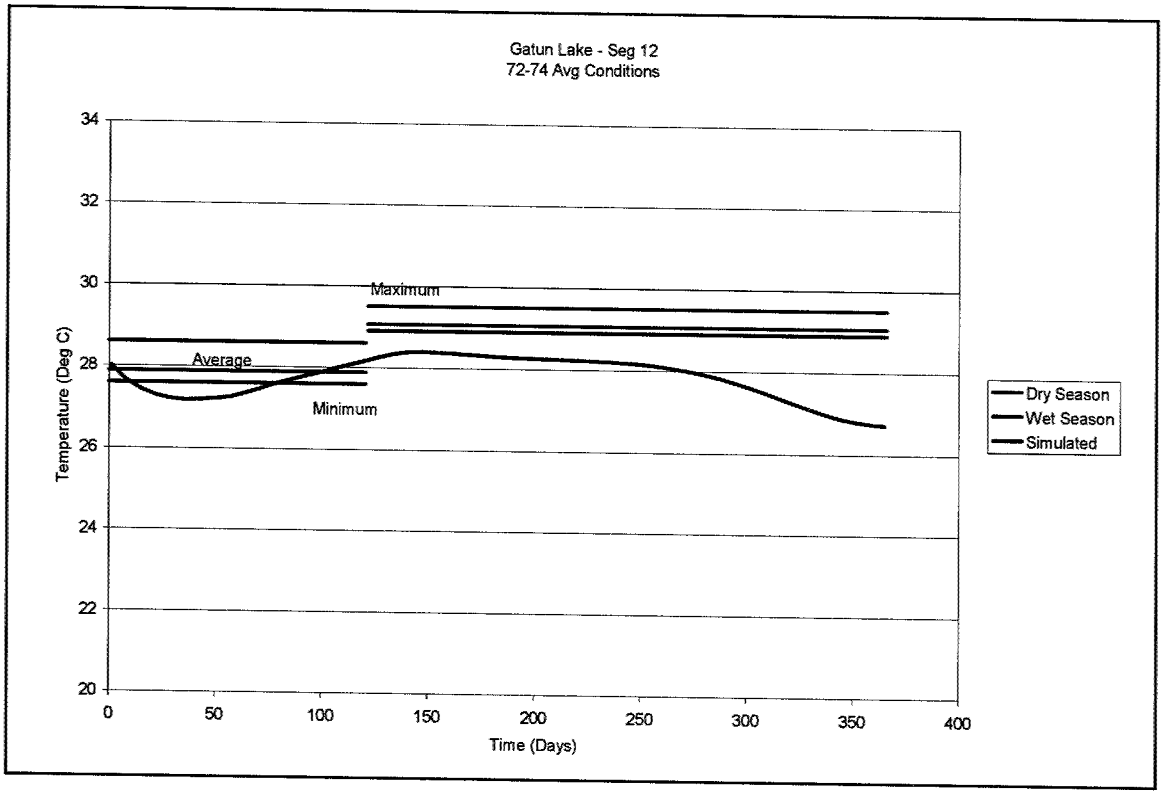

Figure 6-8. Average conditions calibration temperature, segment 12

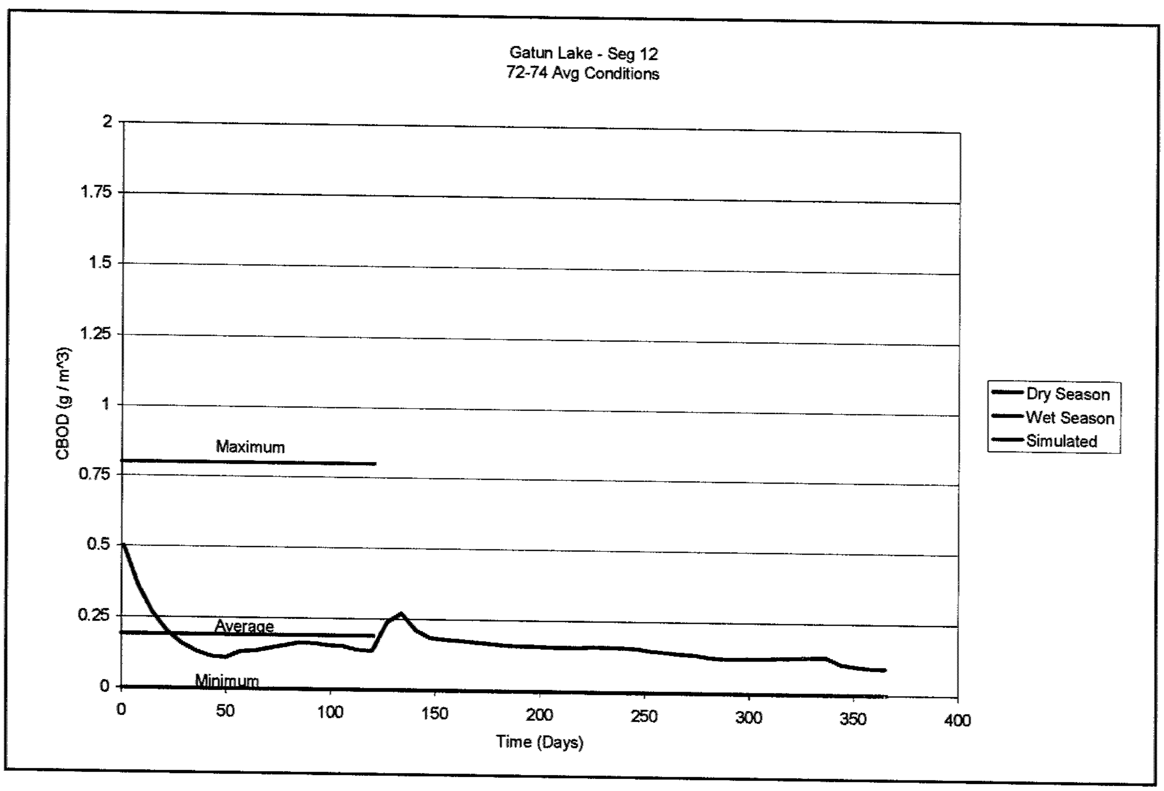

Figure 6-9. Average conditions calibration CBOD, segment 12

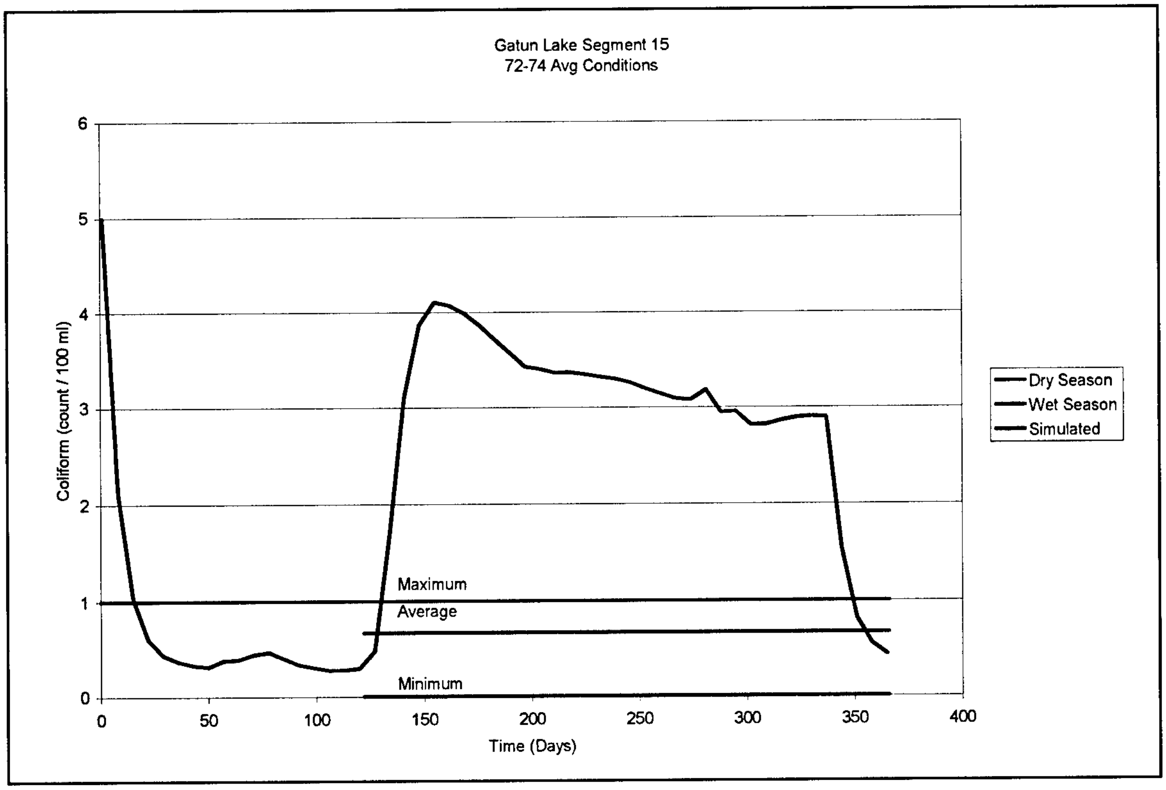

Figure 6-10. Average conditions calibration coliform, segment 15

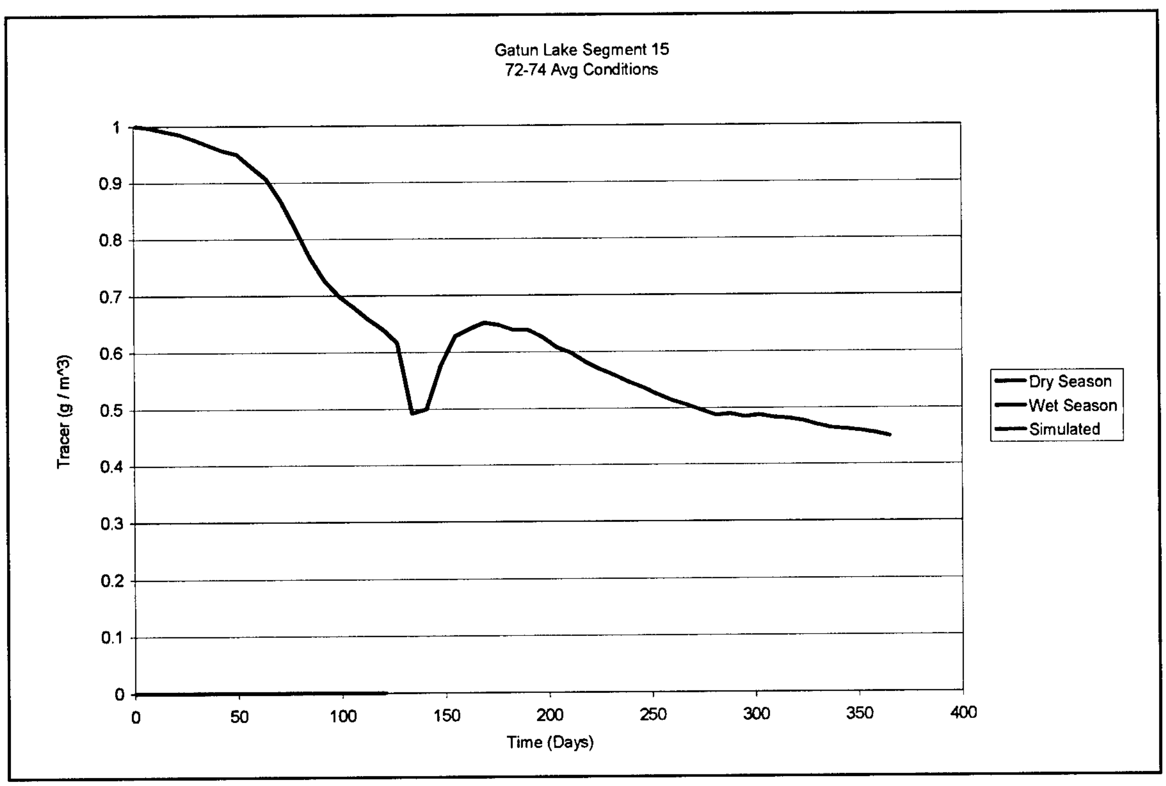

Figure 6-11. Average condition calibration tracer, segment 15

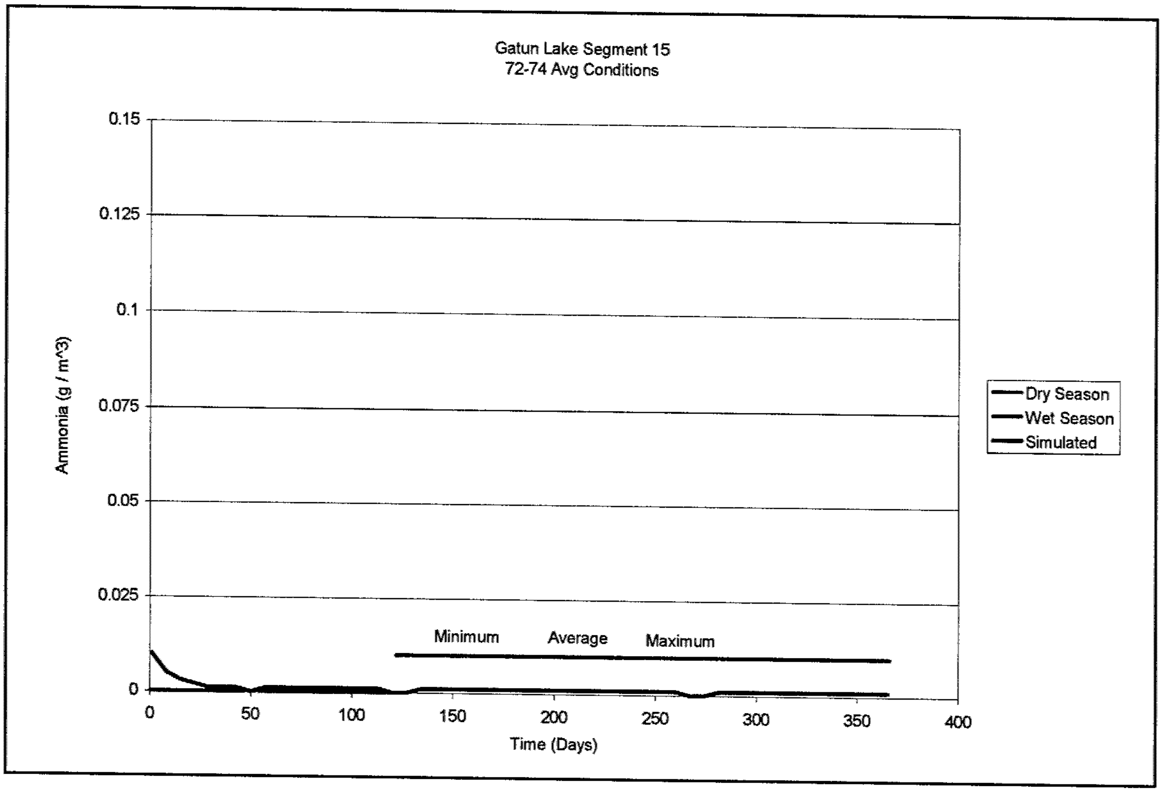

Figure 6-12. Average calibration conditions ammonia, segment 15

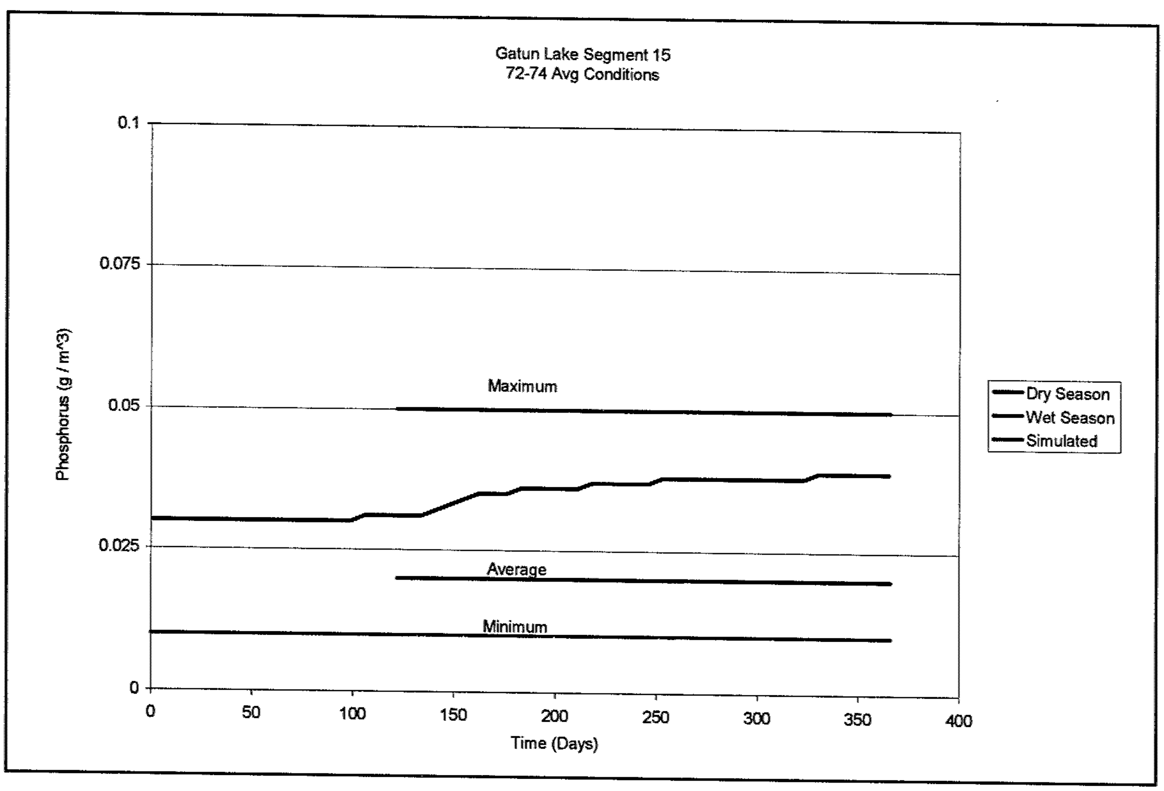

Figure 6-13. Average calibration conditions phosphorus, segment 15

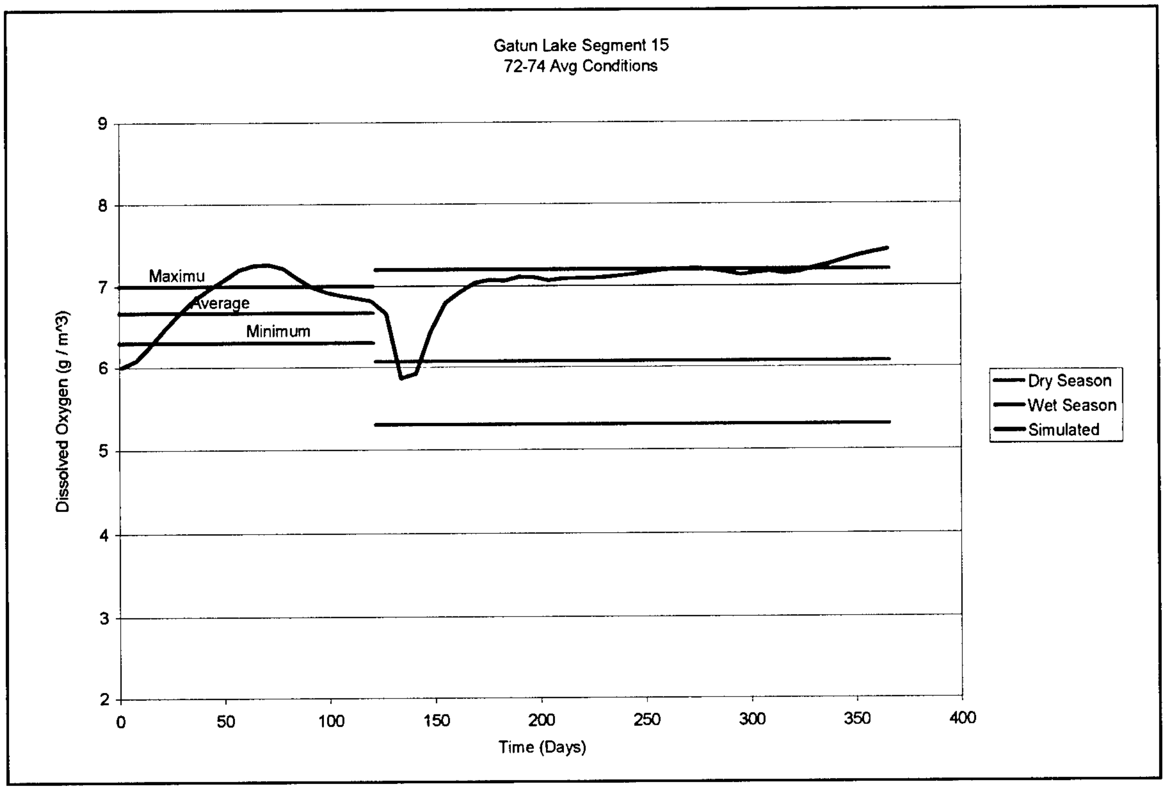

Figure 6-14. Average conditions calibration dissolved oxygen, segment 15

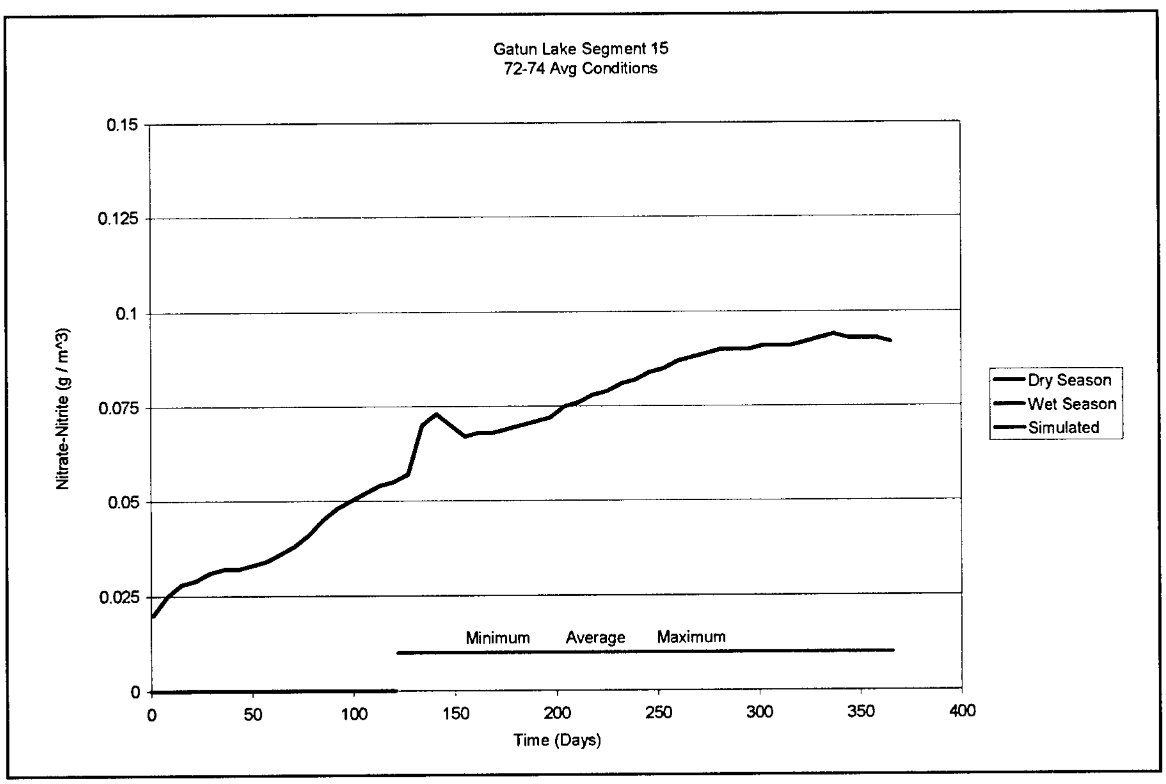

Figure 6-15. Average conditions calibration nitrite-nitrate, segment 15

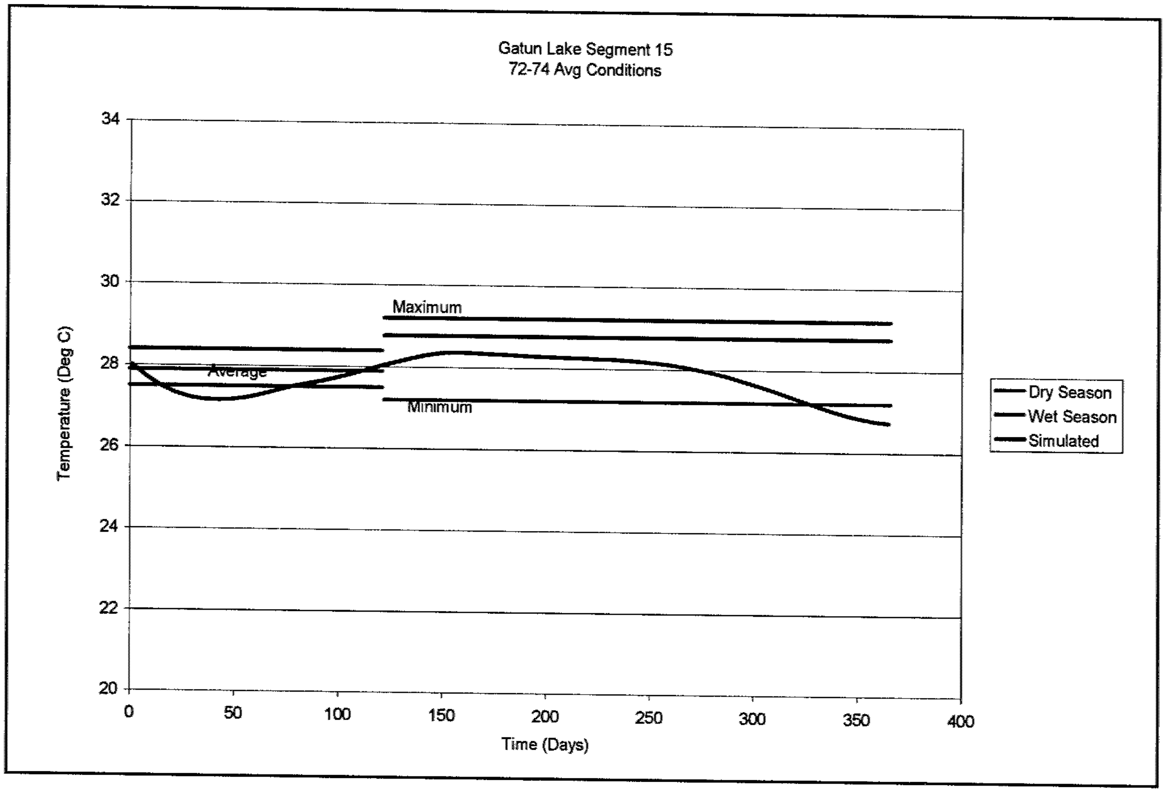

Figure 6-16. Average conditions calibration temperature, segment 15

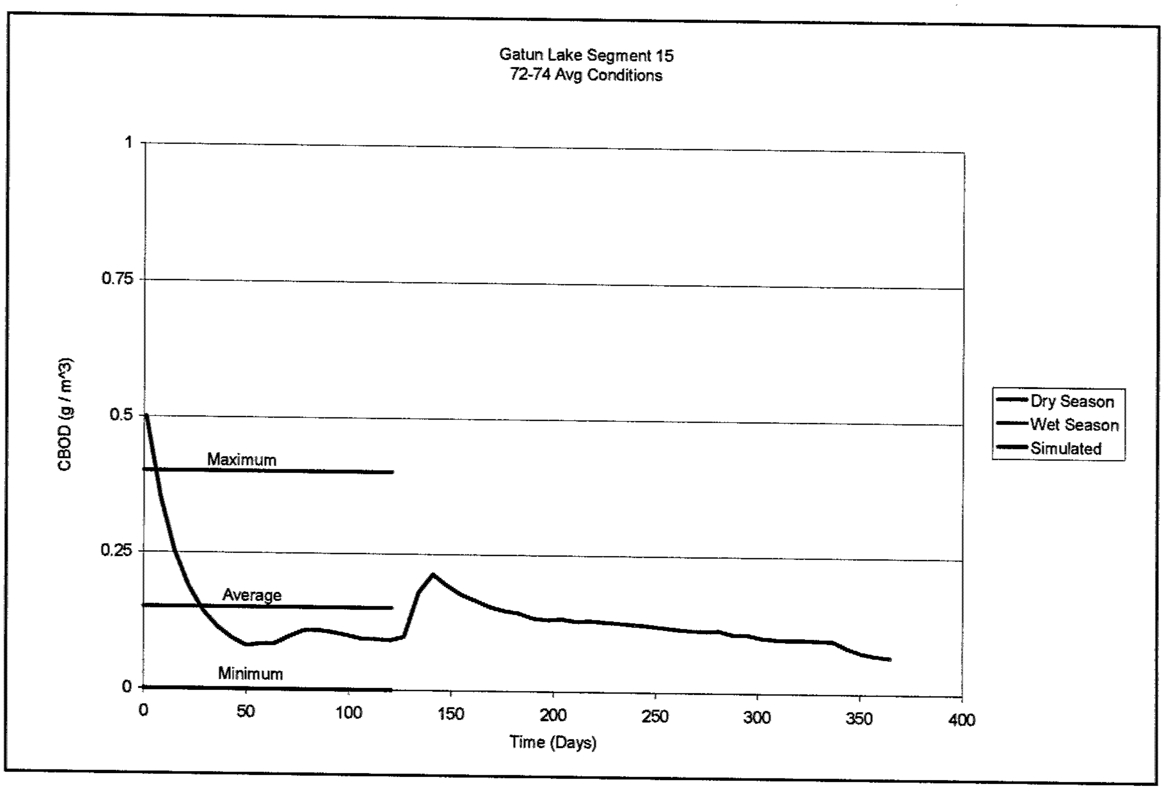

Figure 6-17. Average conditions calibration cbod, segment 15

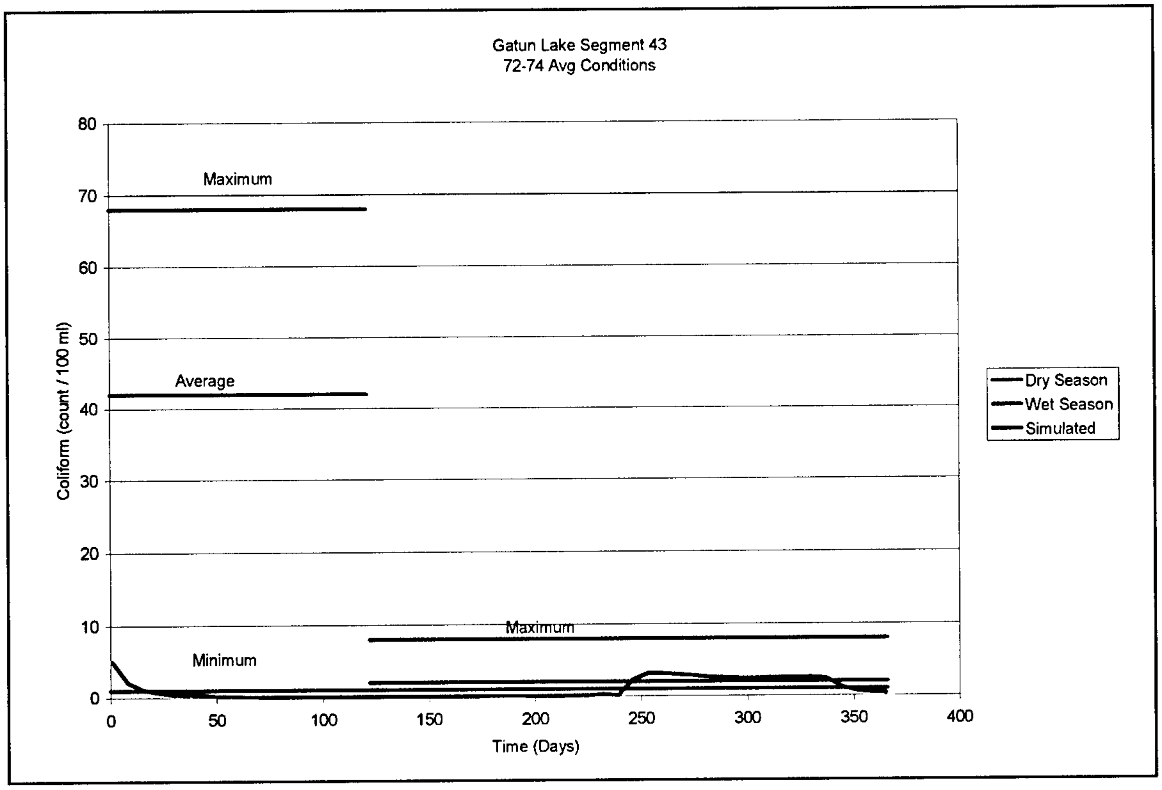

Figure 6-18. Average conditions calibration coliform, segment 43

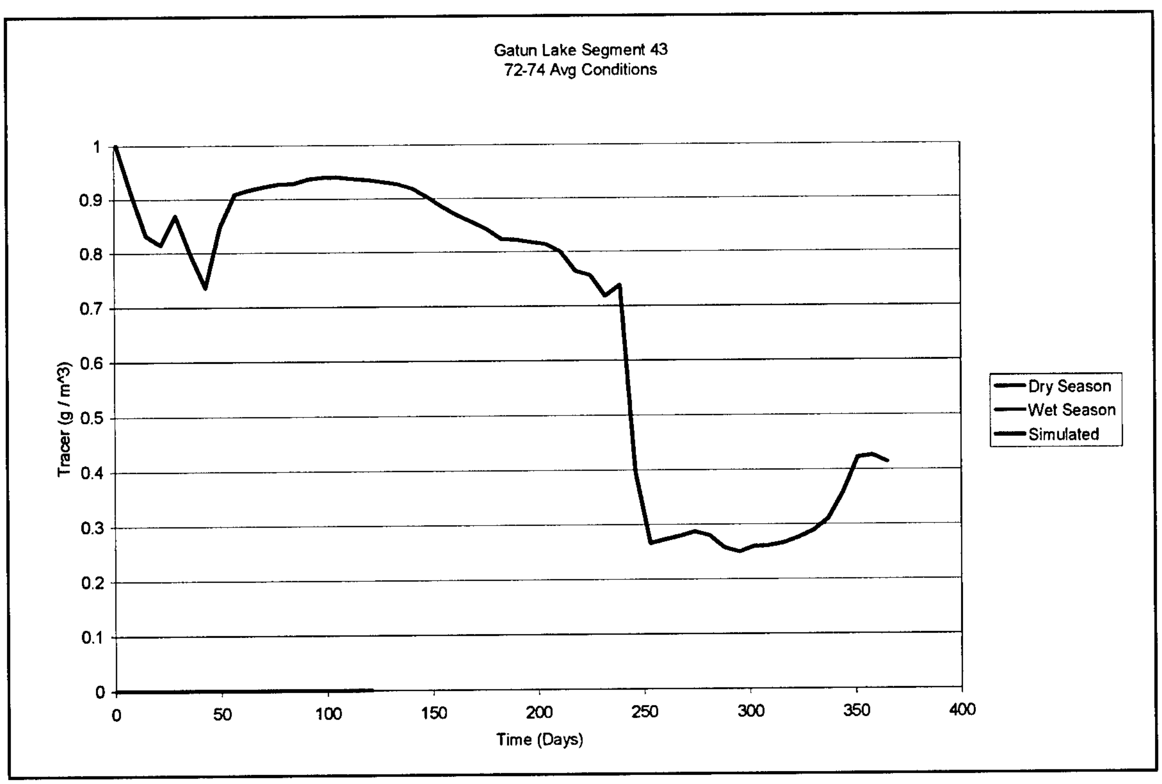

Figure 6-19. Average conditions calibration tracer, segment 43

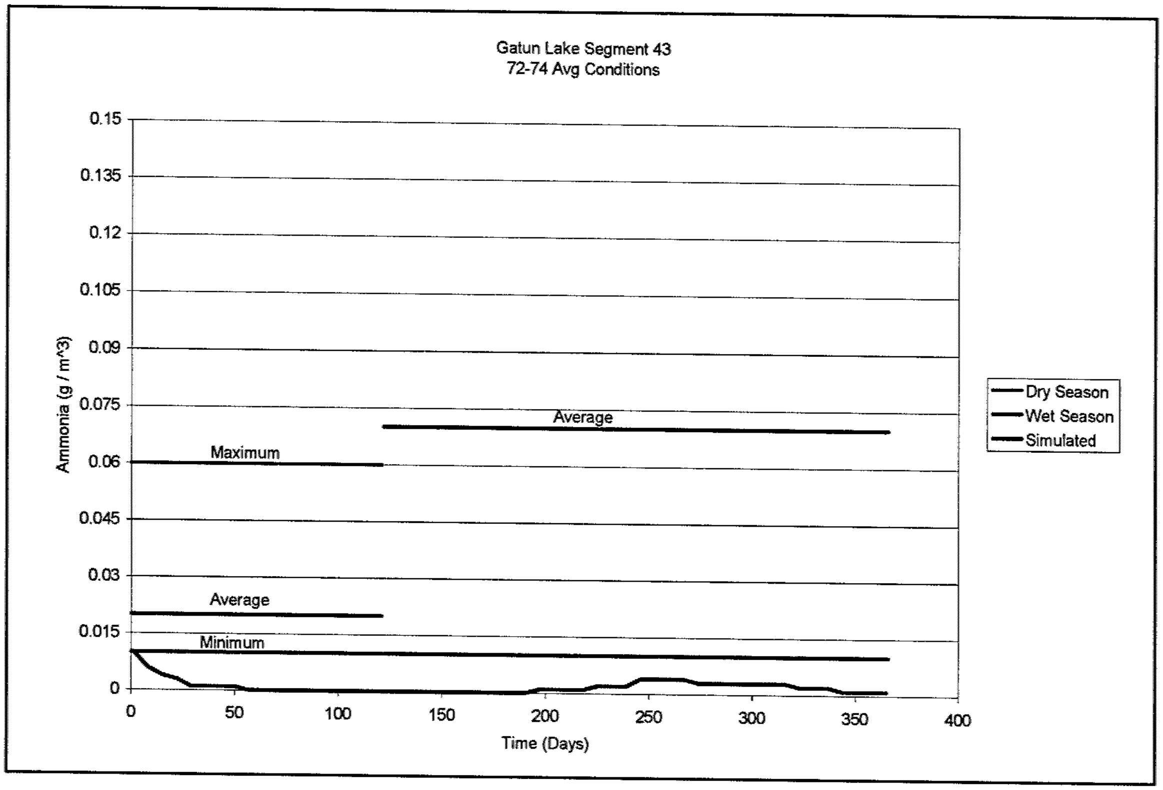

Figure 6-20. Average conditions calibration ammonia, segment 43

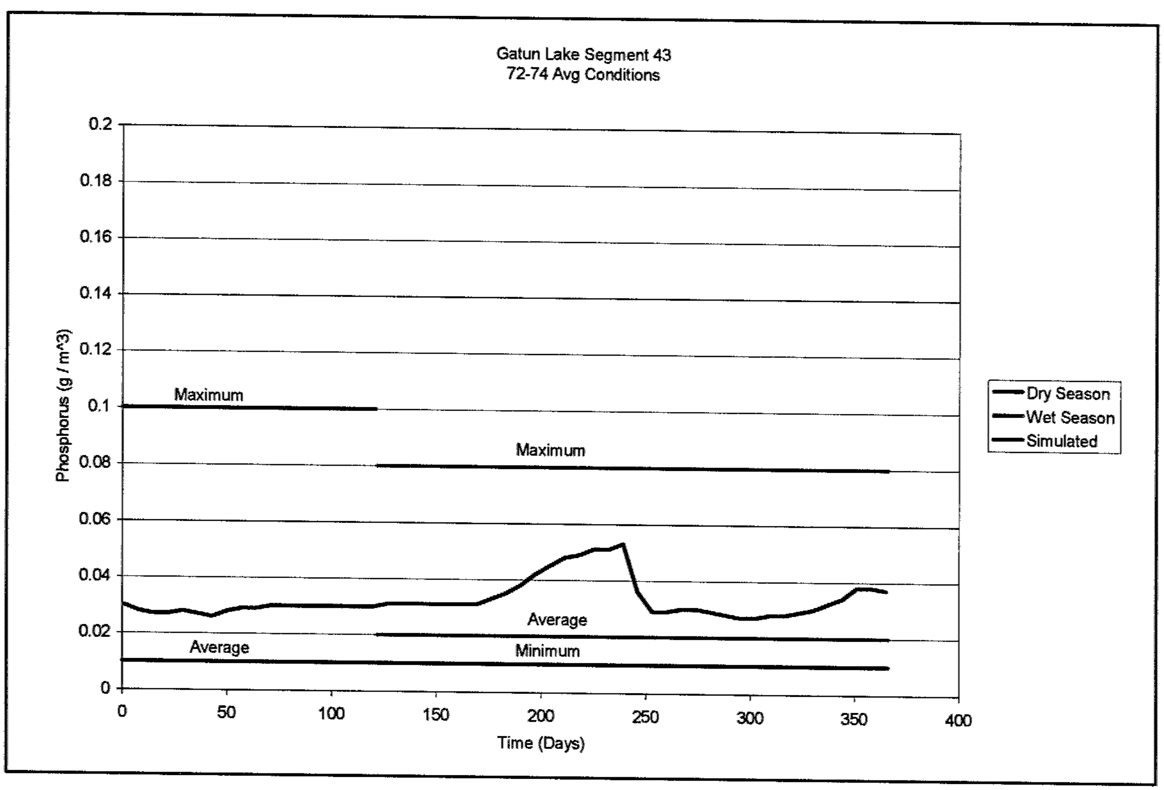

Figure 6-21. Average conditions calibration phosphorus, segment 43

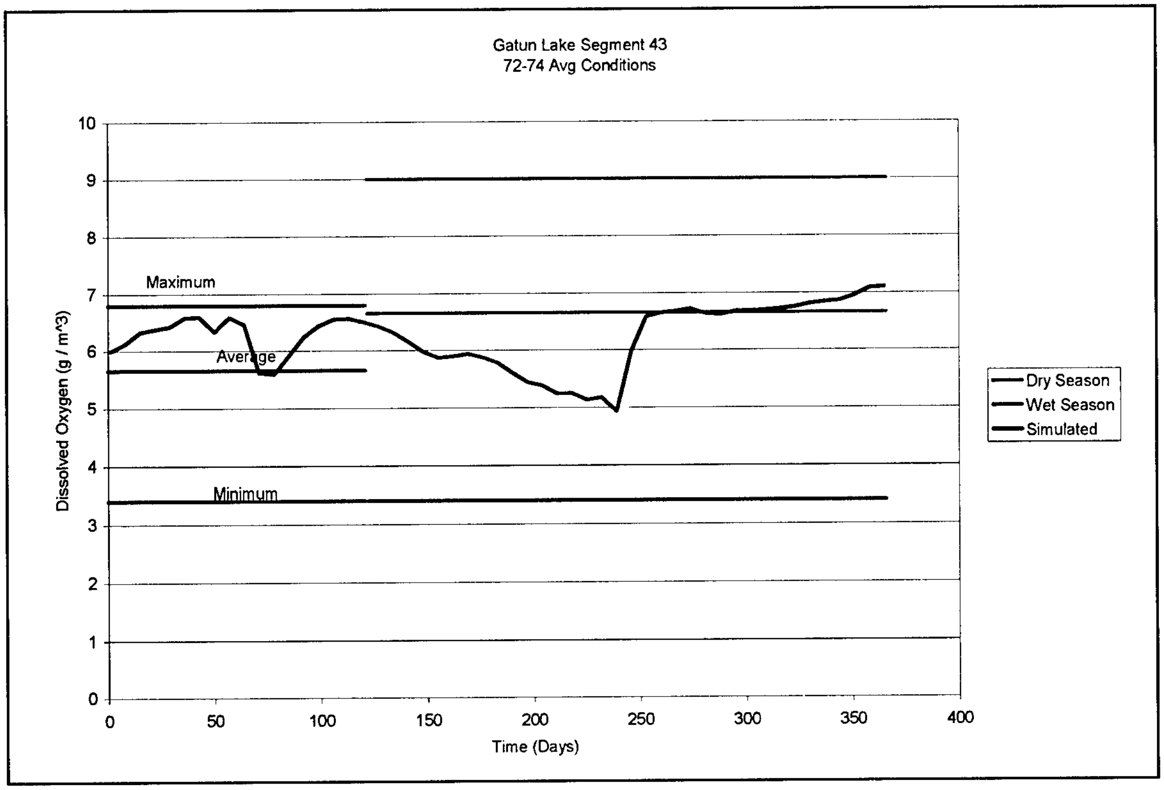

Figure 6-22. Average conditions calibration dissolved oxygen, segment 43

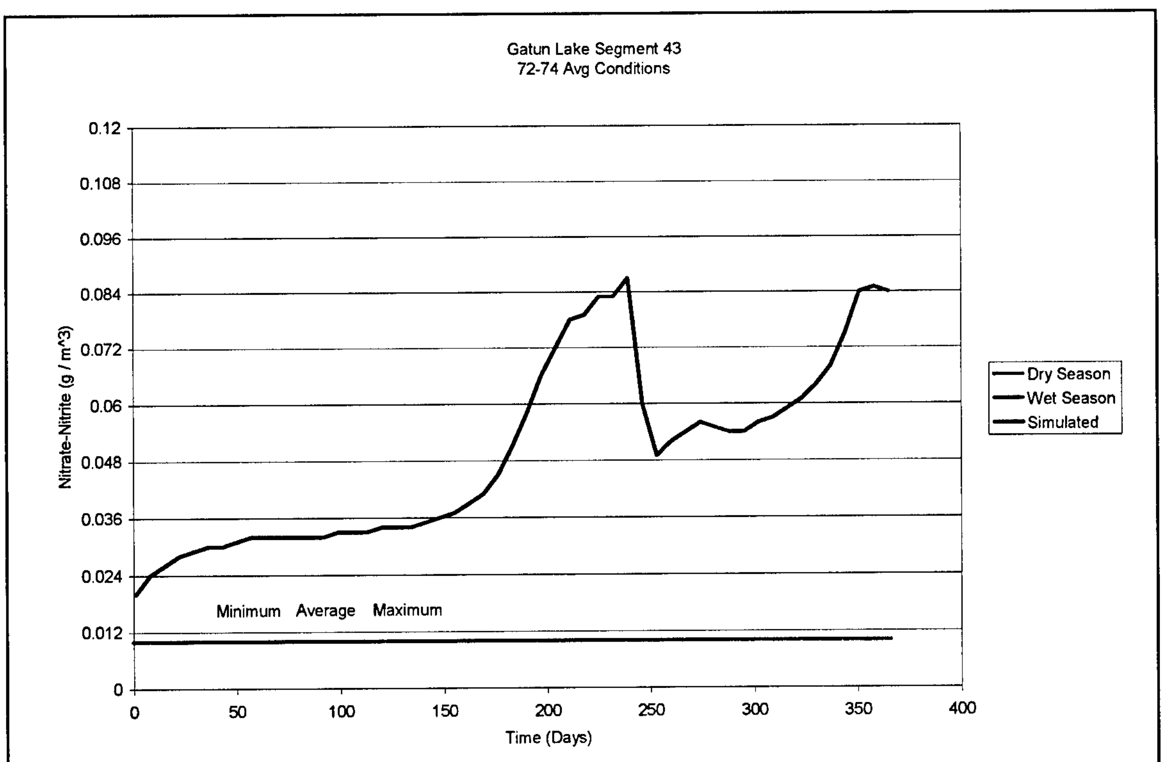

Figure 6-23. Average conditions calibration nitrite-nitrate, segment 43

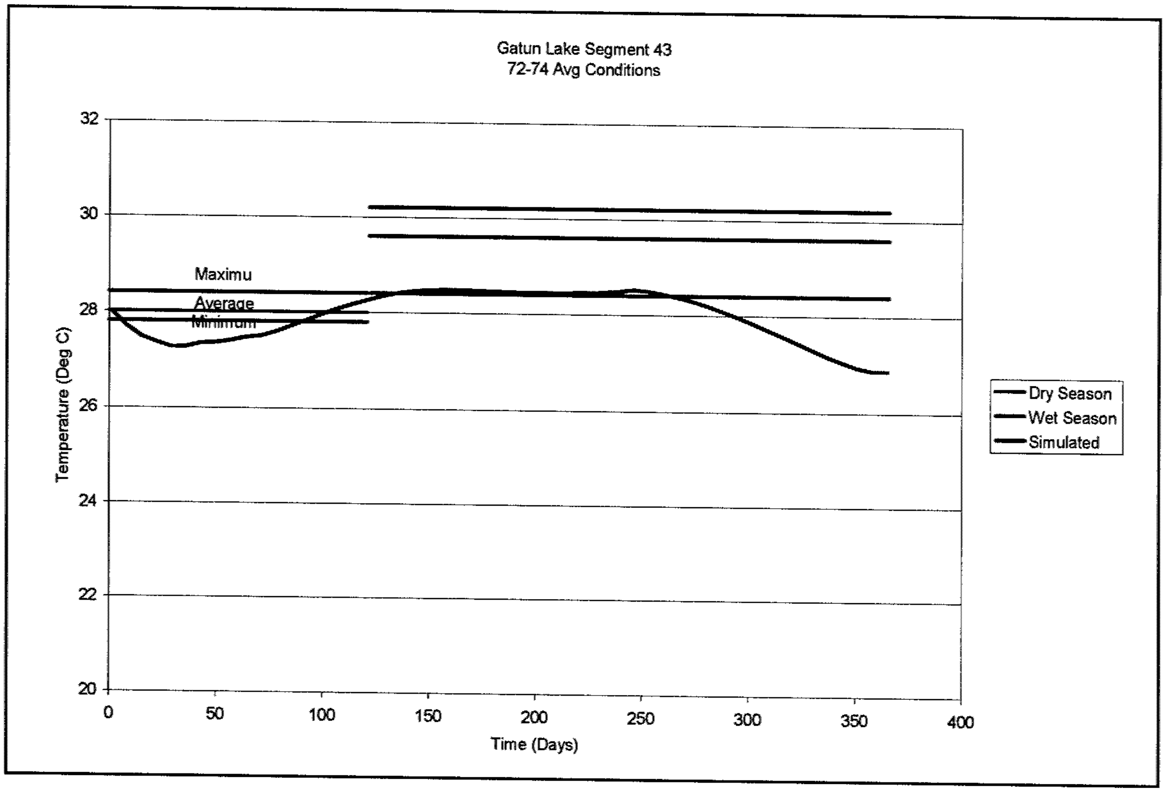

Figure 6-24. Average conditions calibration temperature, segment 43

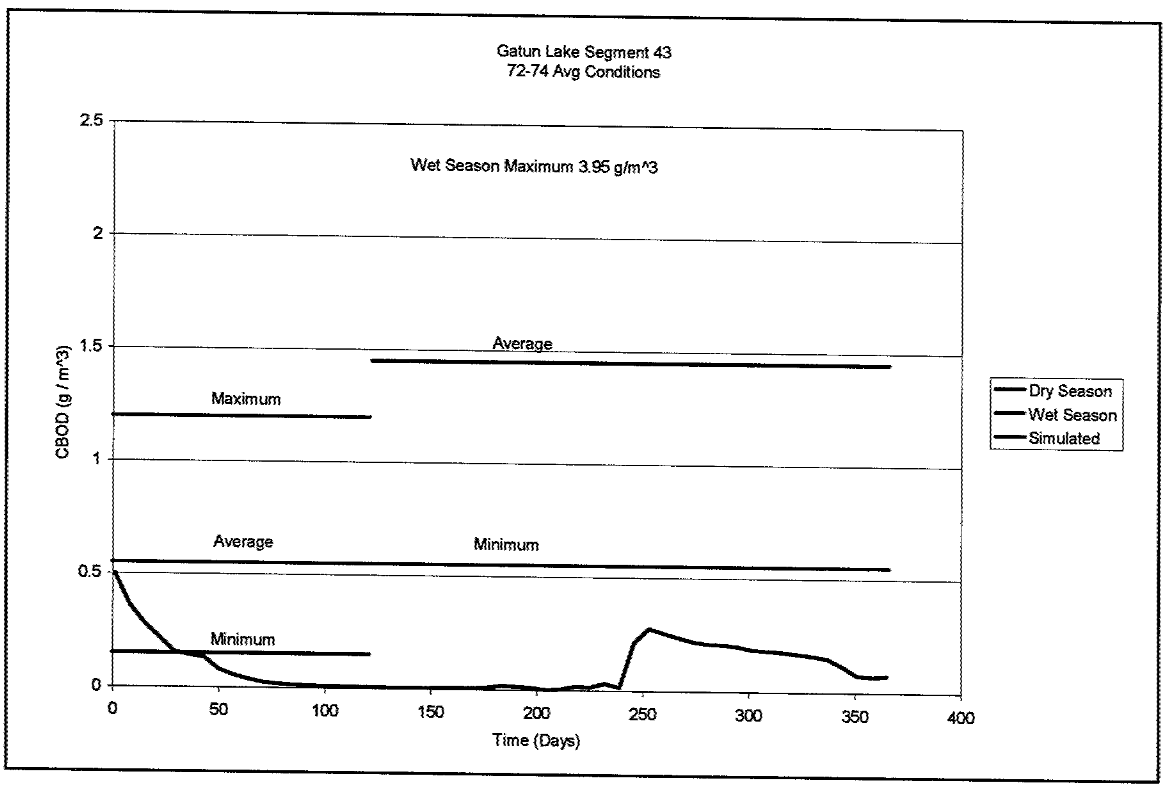

Figure 6-25. Average conditions calibration cbod, segment 43

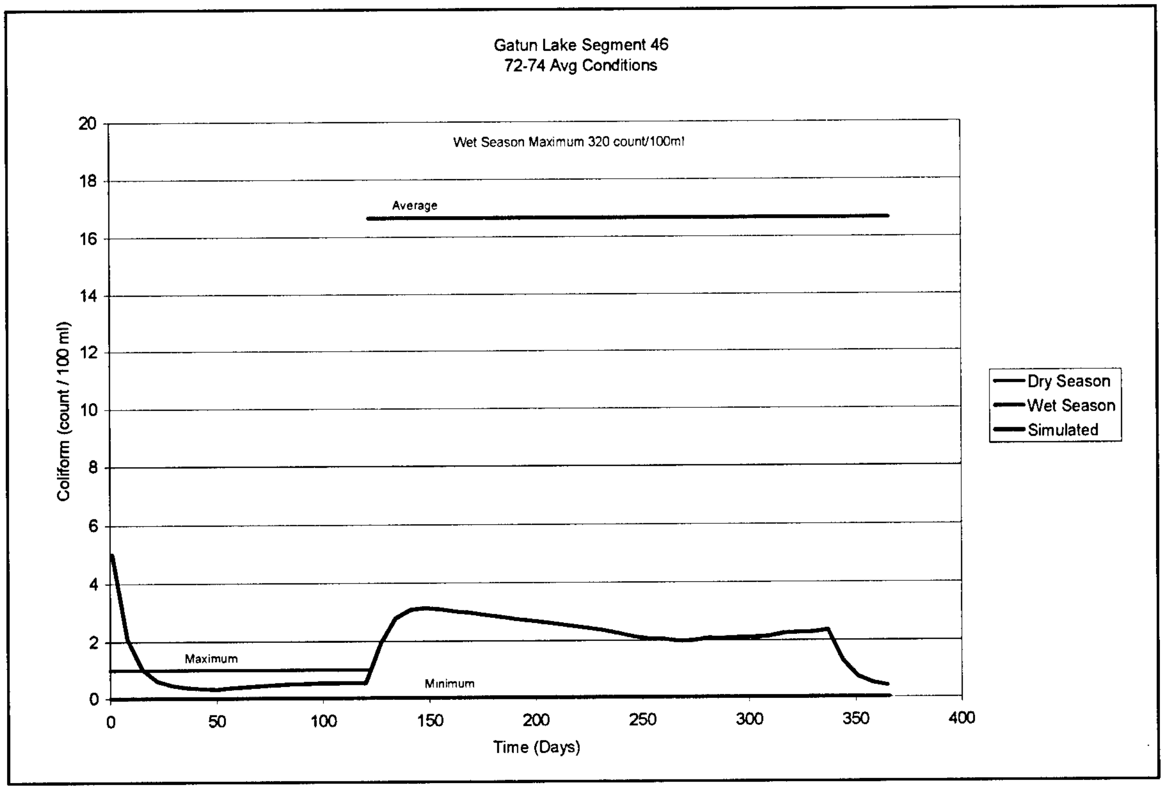

Figure 6-26. Average conditions calibration coliform, segment 46

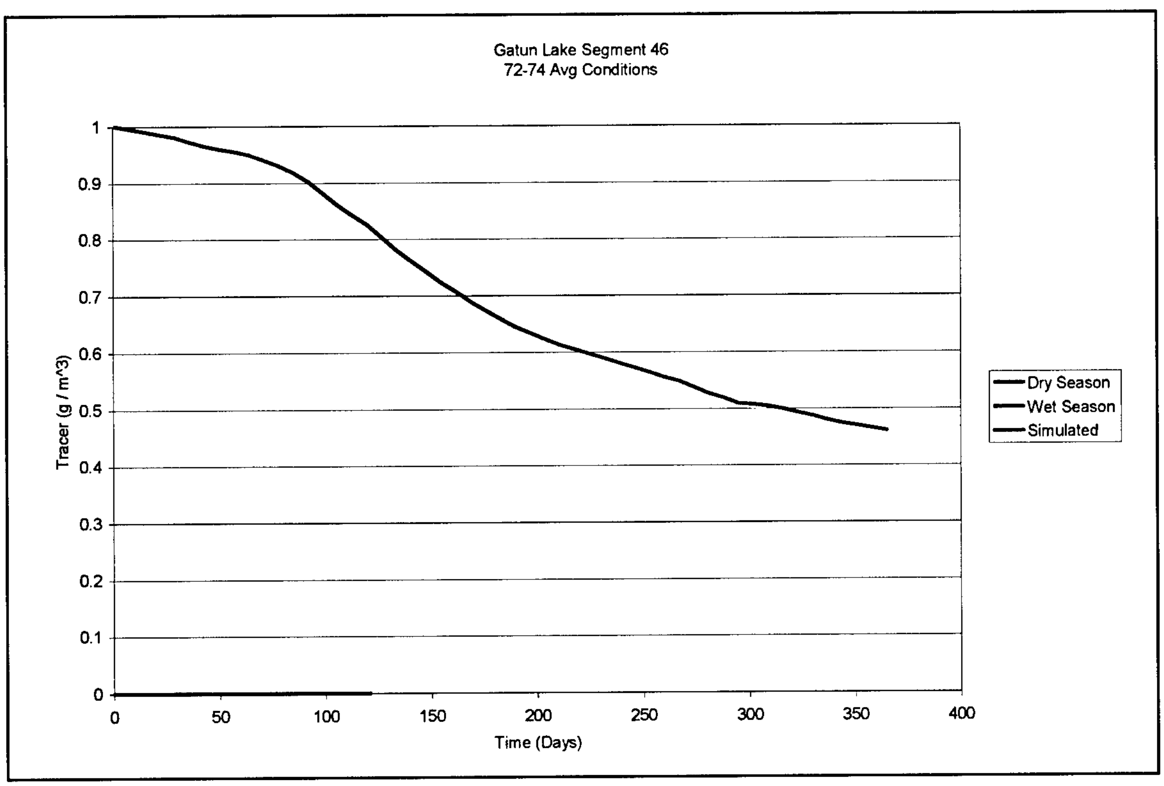

Figure 6-27. Average conditions calibration tracer, segment 46

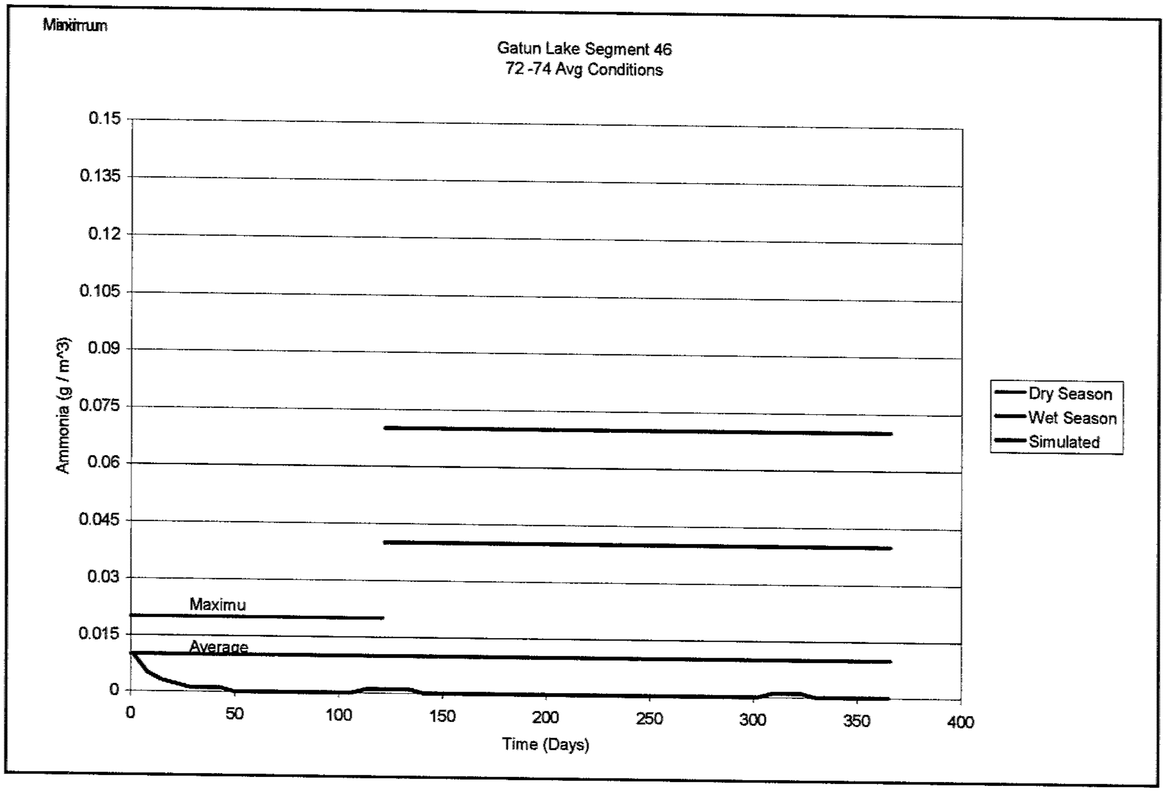

Figure 6-28. Average conditions calibration ammonia, segment 46

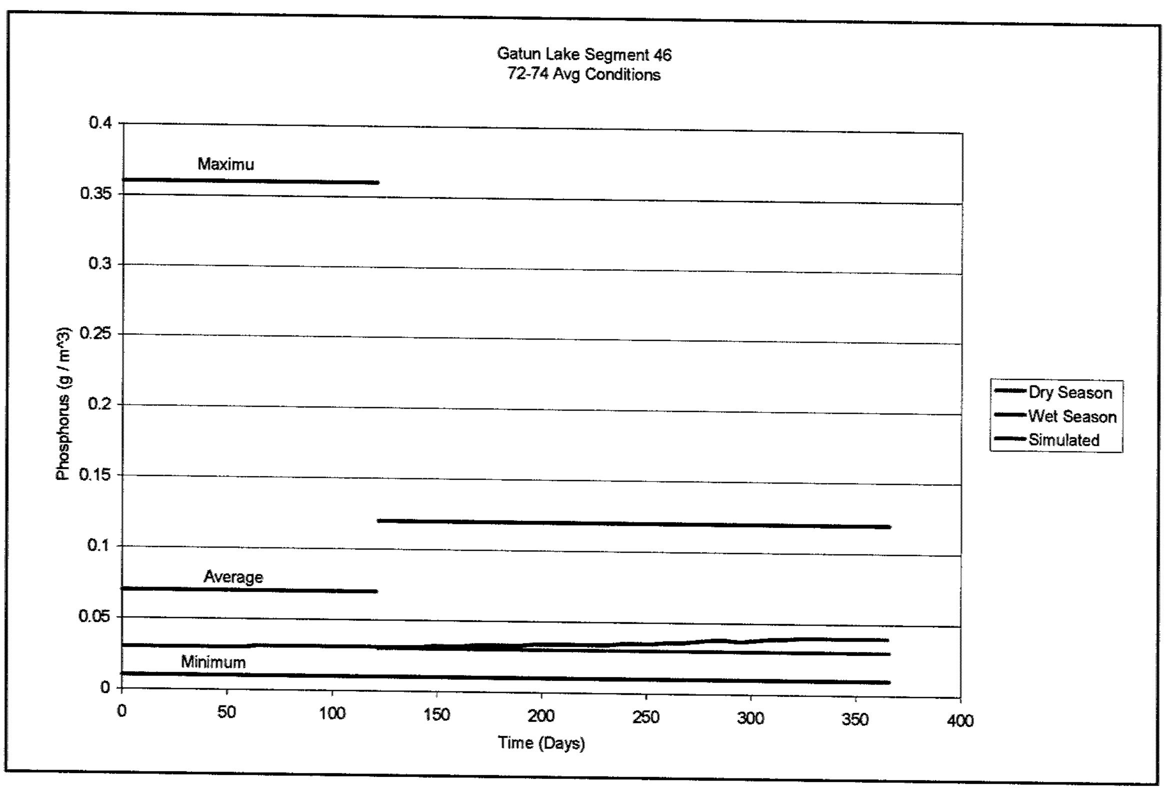

Figure 6-29. Average conditions calibration phosphorus, segment 46

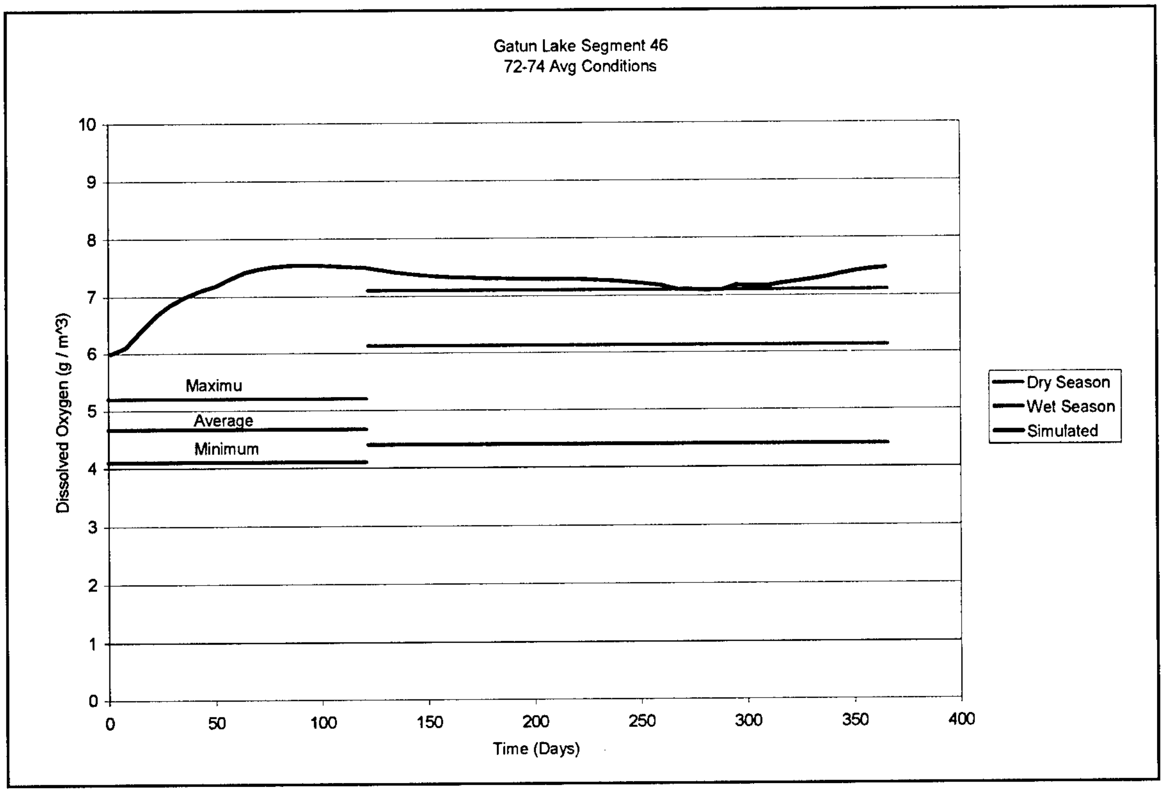

Figure 6-30. Average conditions calibration dissolved oxygen, segment 46

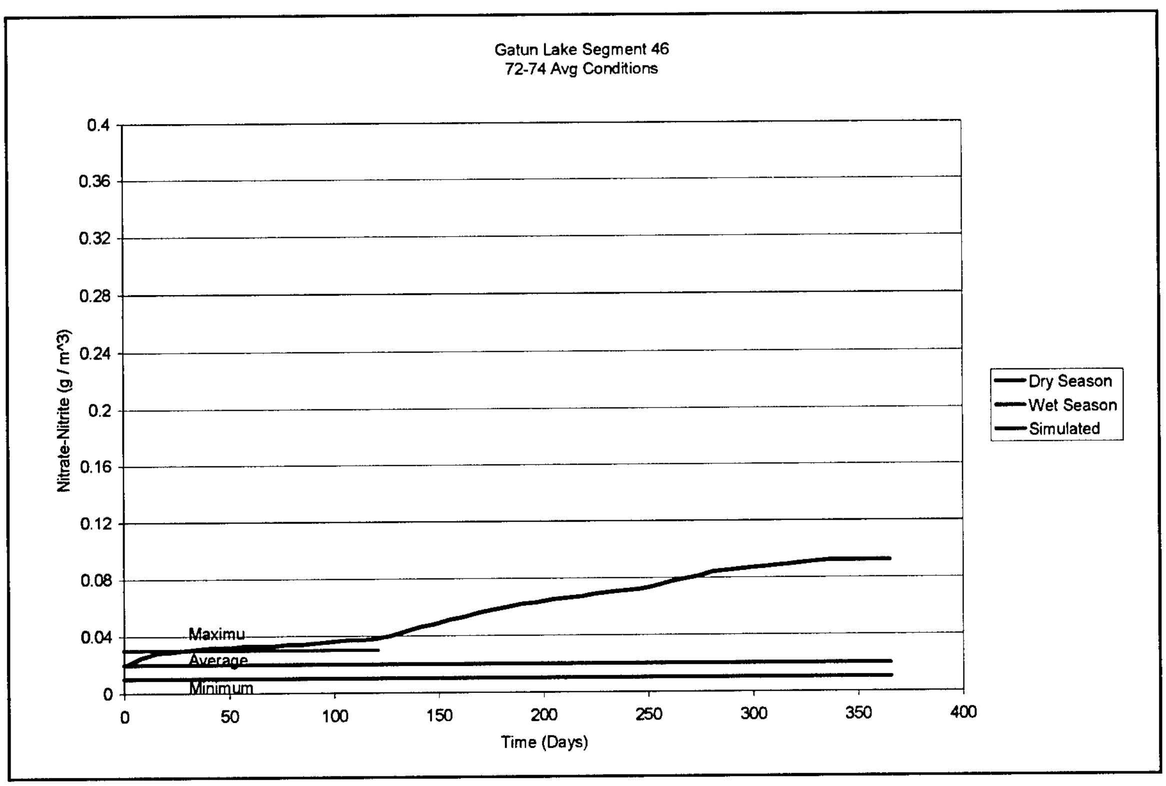

Figure 6-31. Average conditions calibration nitrate, segment 46

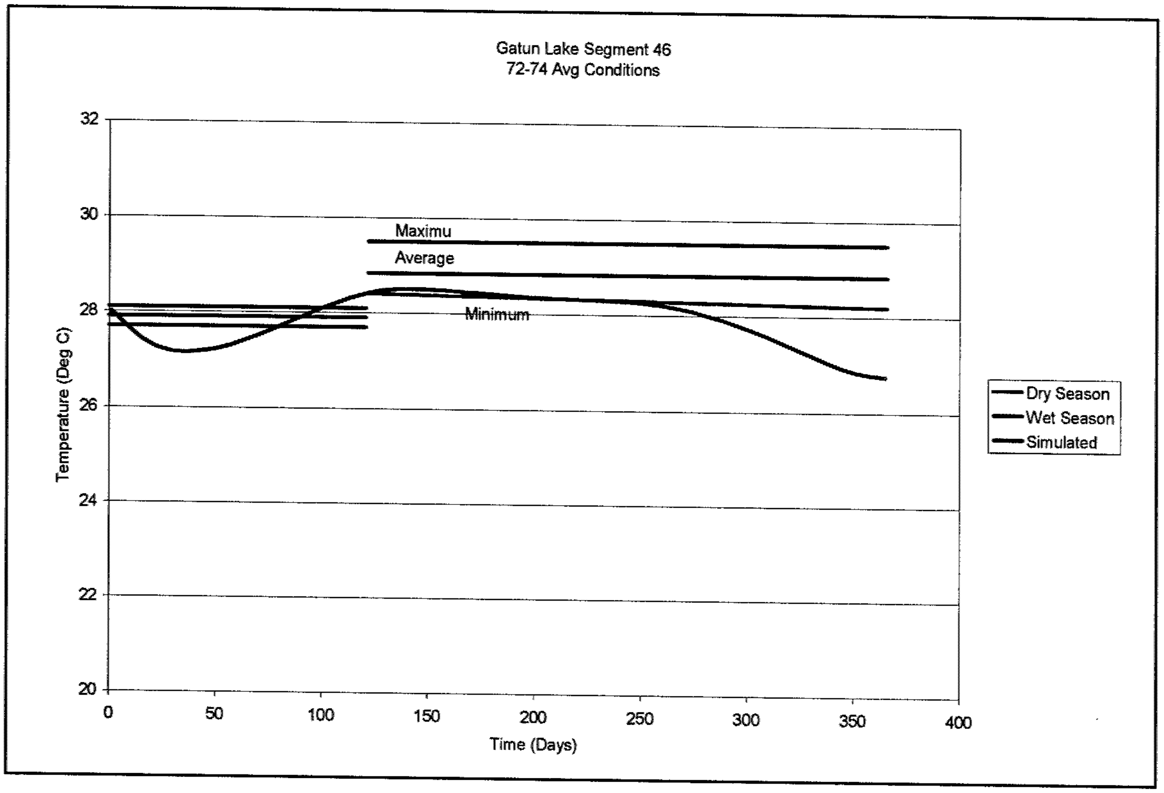

Figure 6-32. Average conditions calibration temperature, segment 46

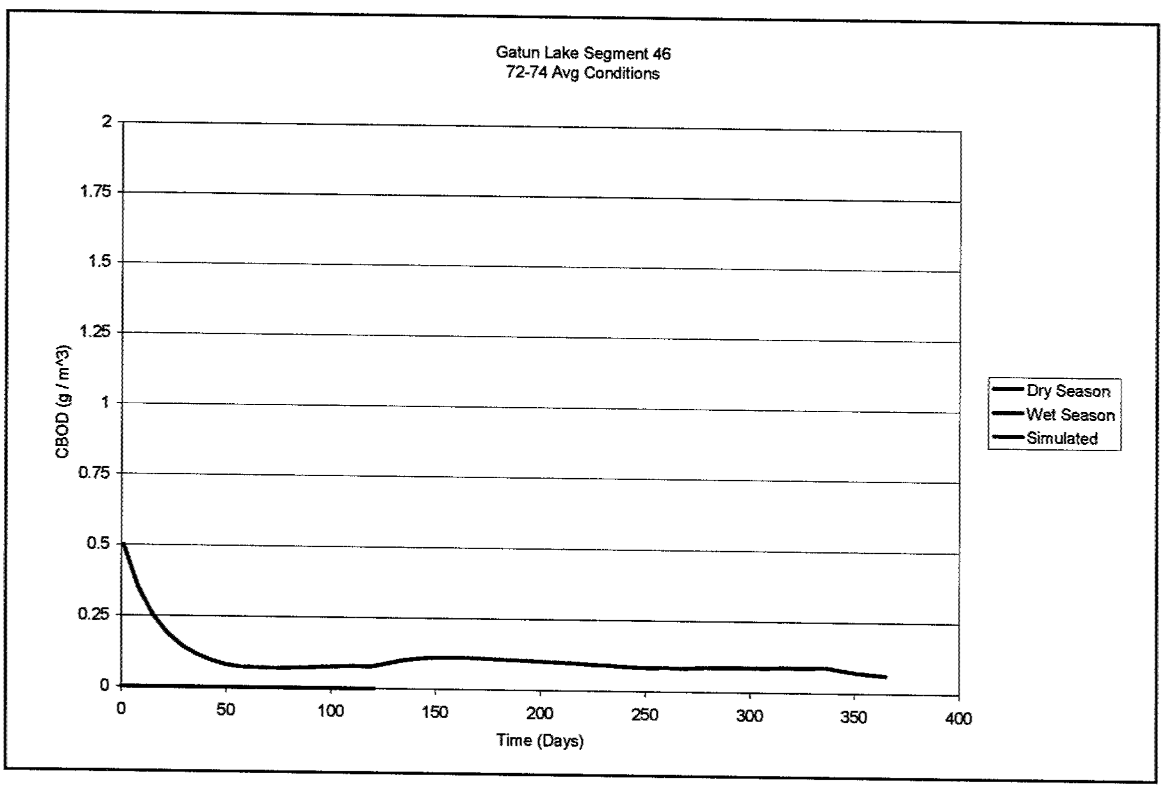

Figure 6-33. Average conditions calibration cbod, segment 46

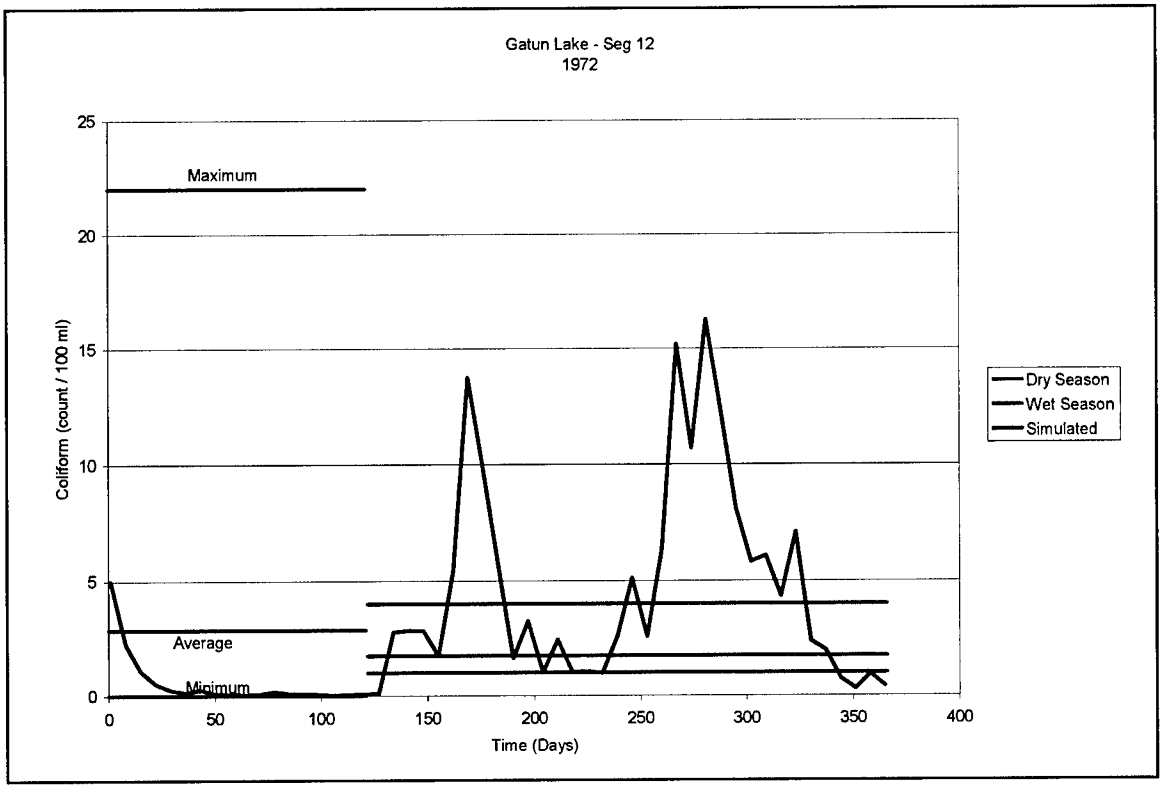

Figure 6-34. 1972 calibration coliform , segment 12

Figure 6-35. 1972 calibration, tracer

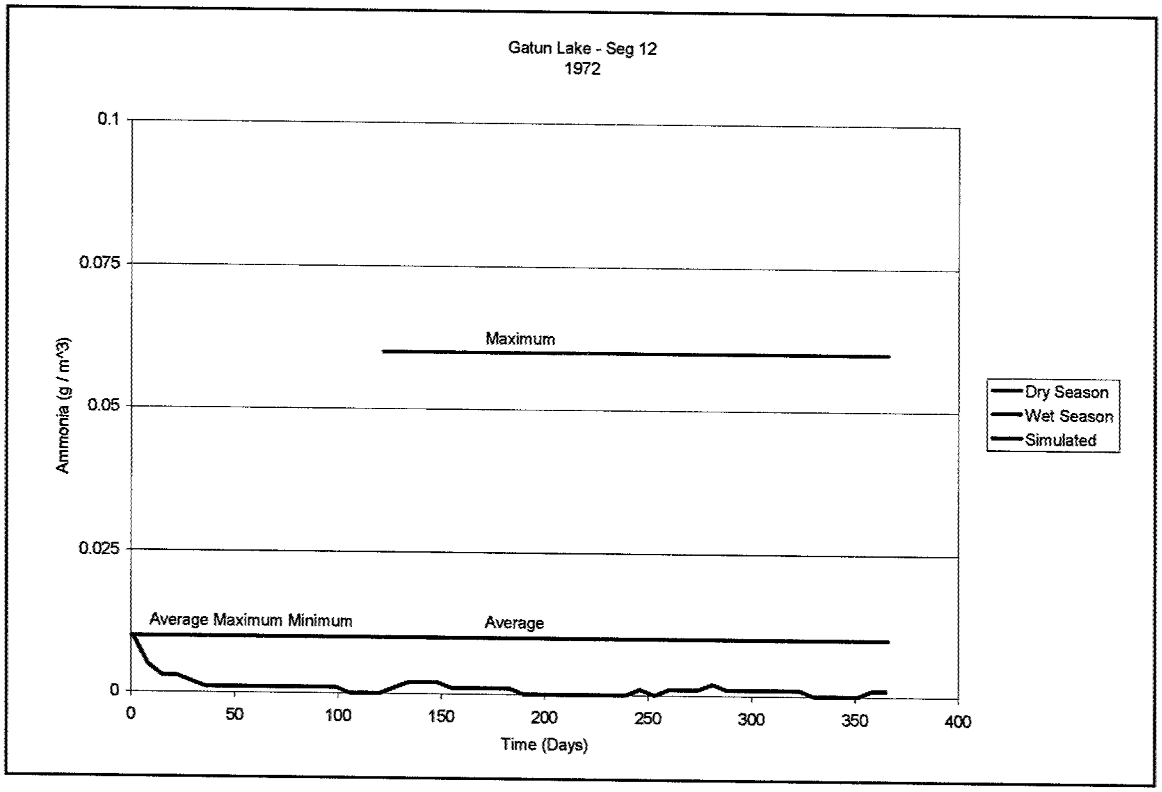

Figure 6-36. 1972 calibration, ammonia, segment 12

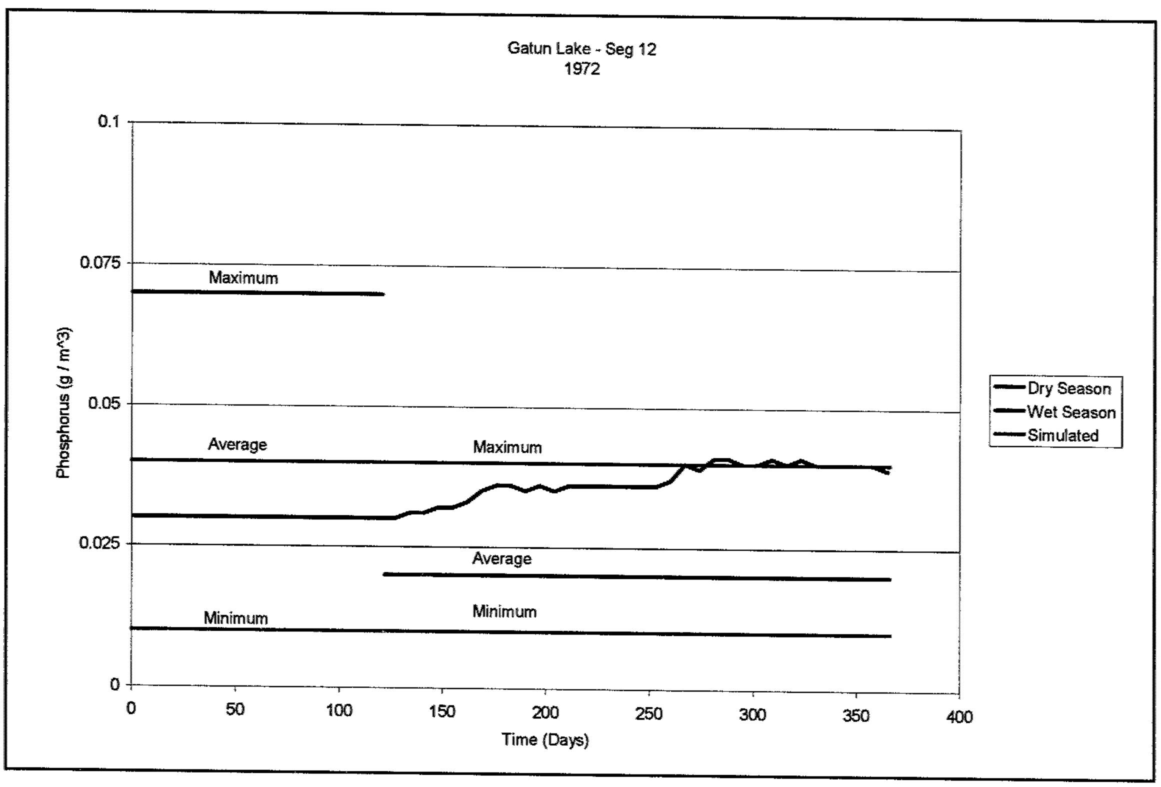

Figure 6-37. 1972 calibration, phosphorus, segment 12

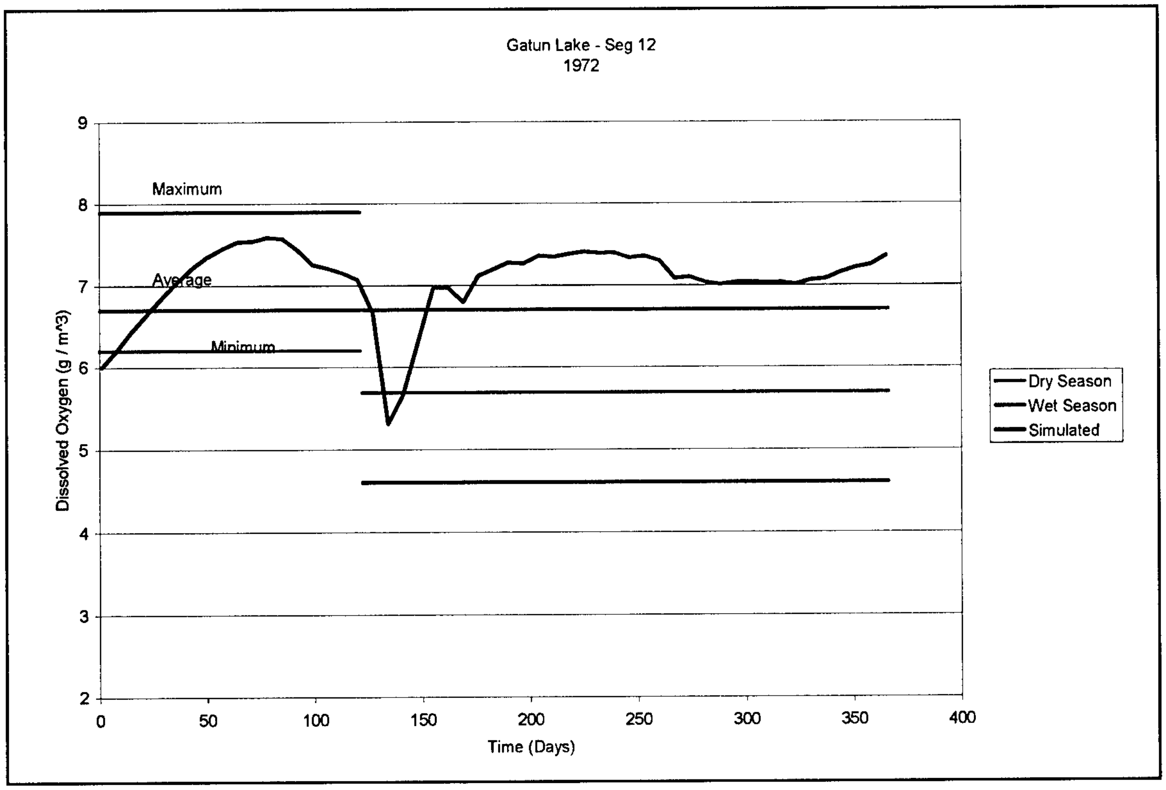

Figure 6-38. 1972 calibration, dissolved oxygen, segment 12

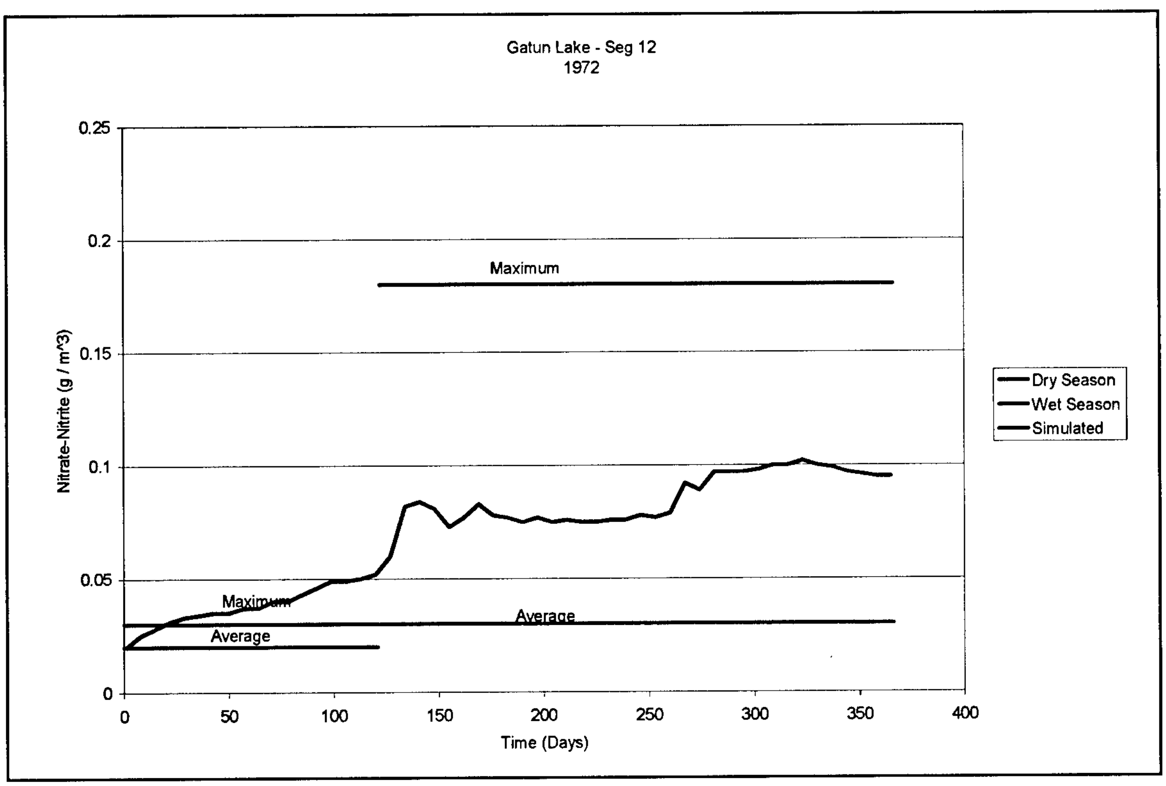

Figure 6-39. 1972 calibration, nitrate-nitrite, segment 12

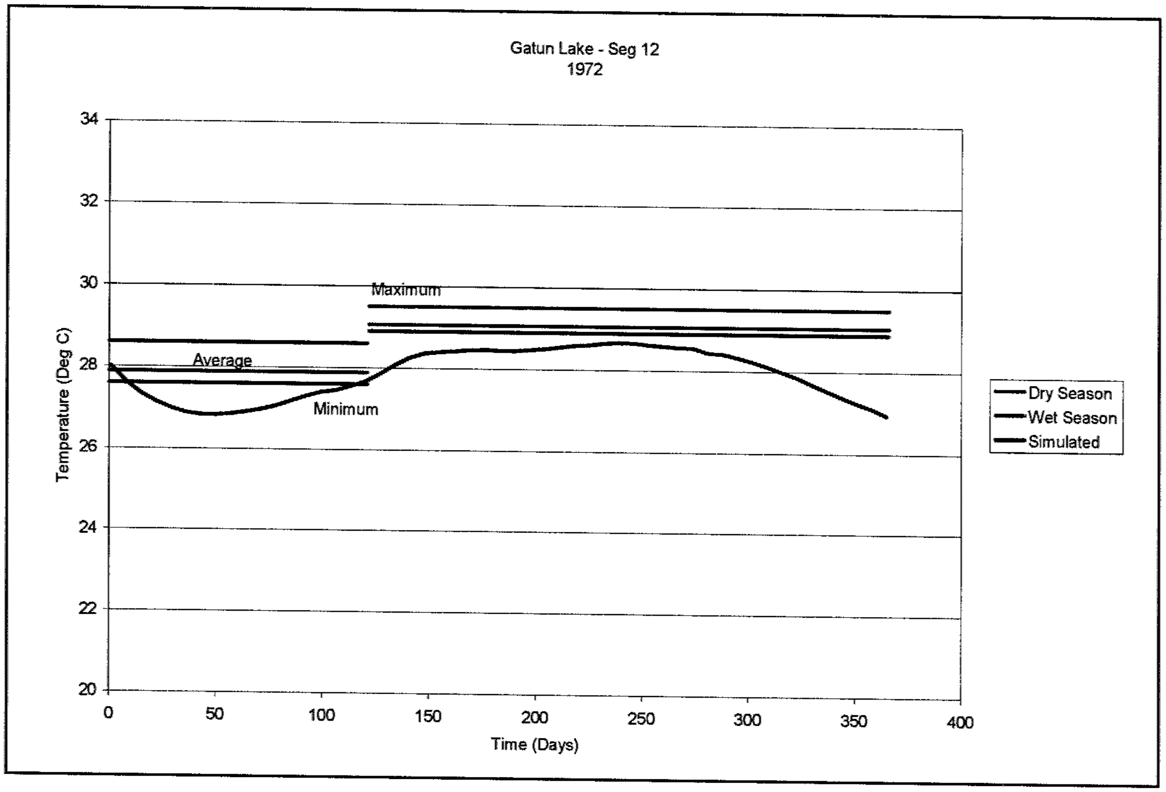

Figure 6-40. 1972 calibration, temperature, segment 12

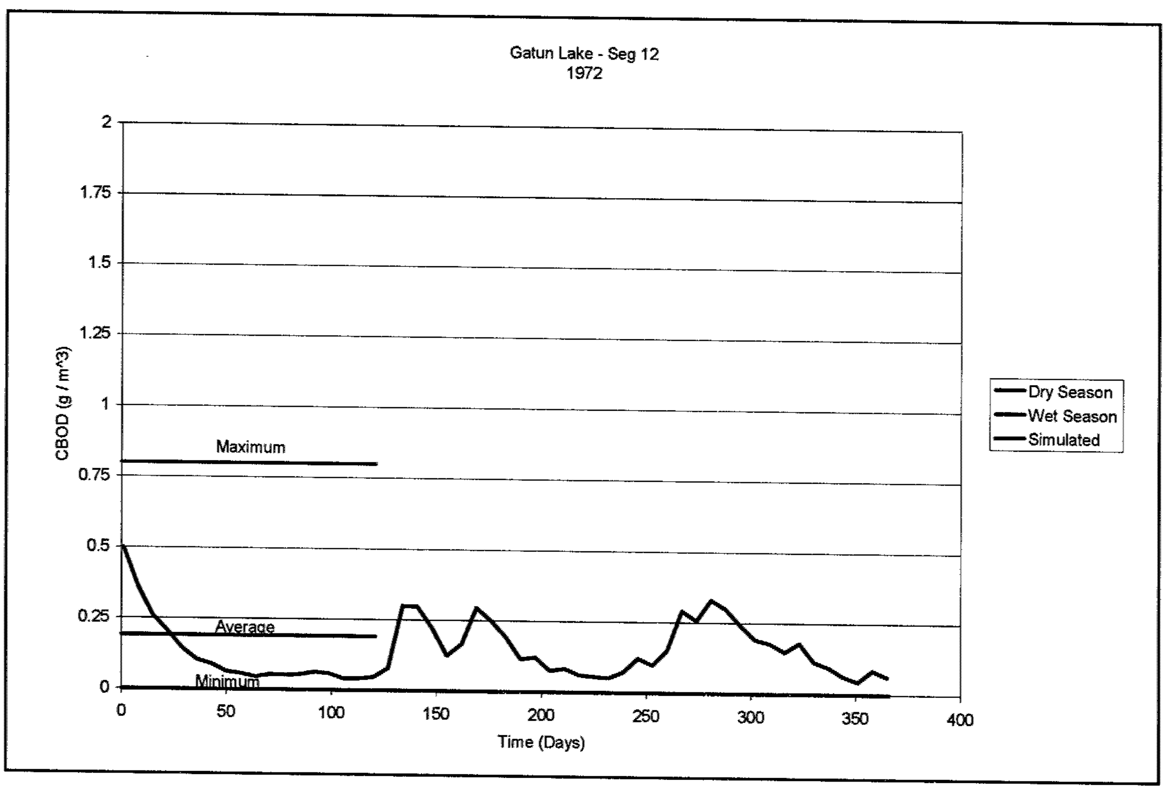

Figure 6-41. 1972 calibration, CBOD, segment 12

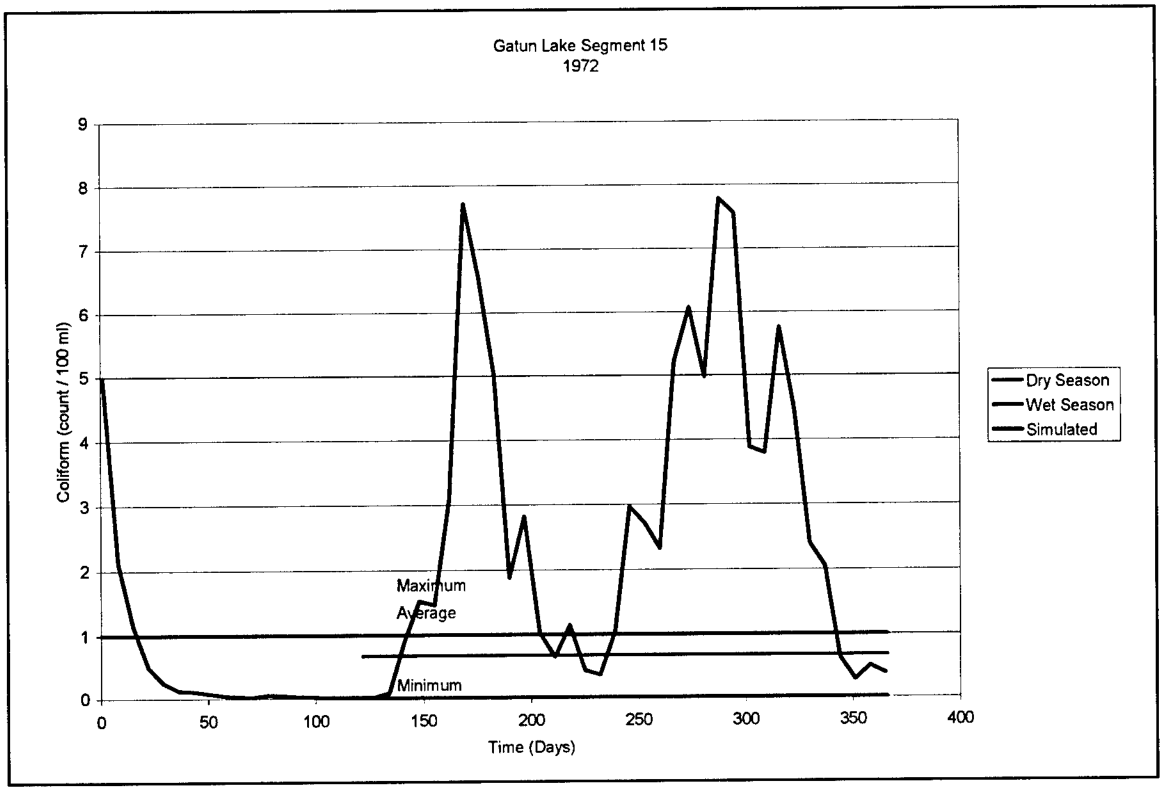

Figure 6-42. 1972 calibration coliform, segment 15

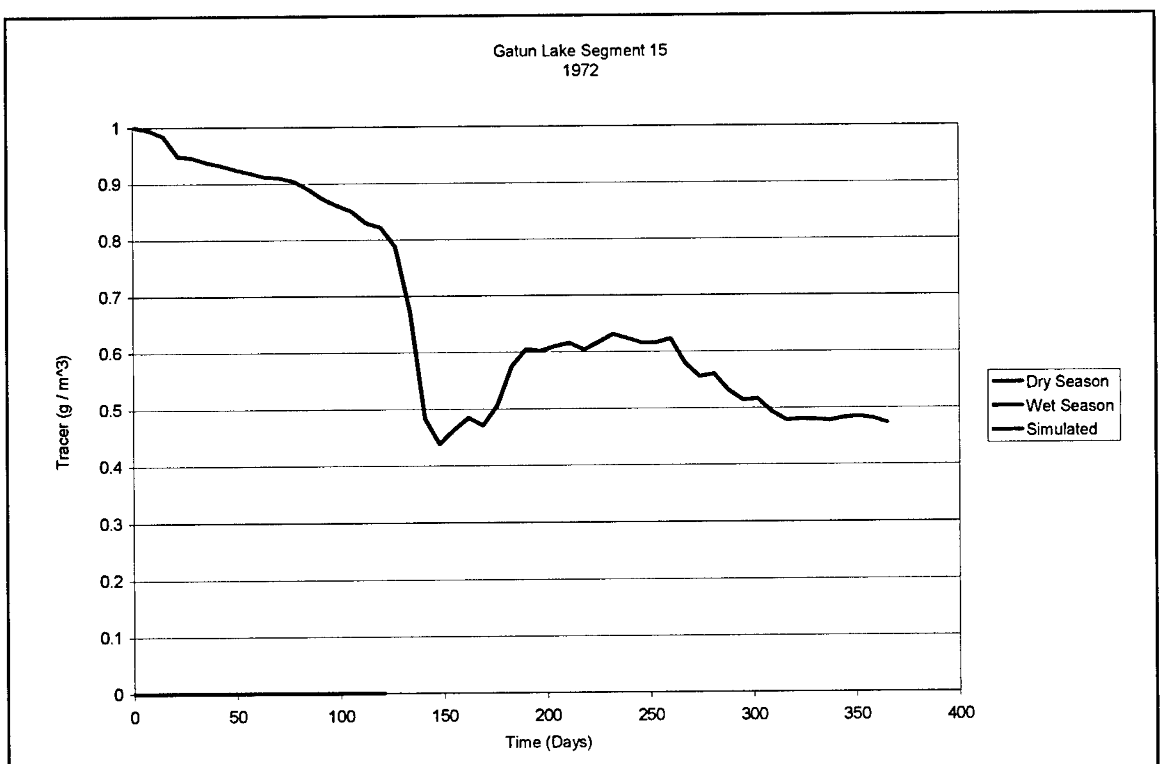

Figure 6-43. 1972 calibration tracer, segment 15

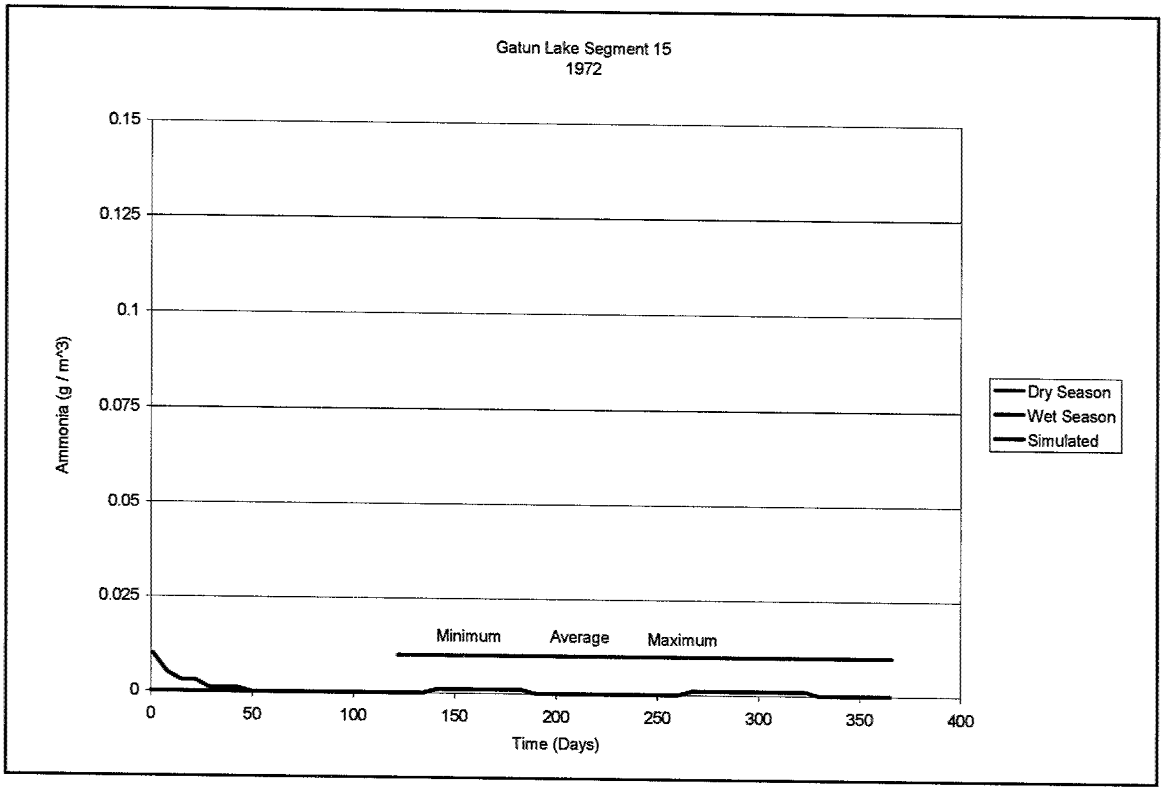

Figure 6-44. 1972 calibration ammonia, segment 15

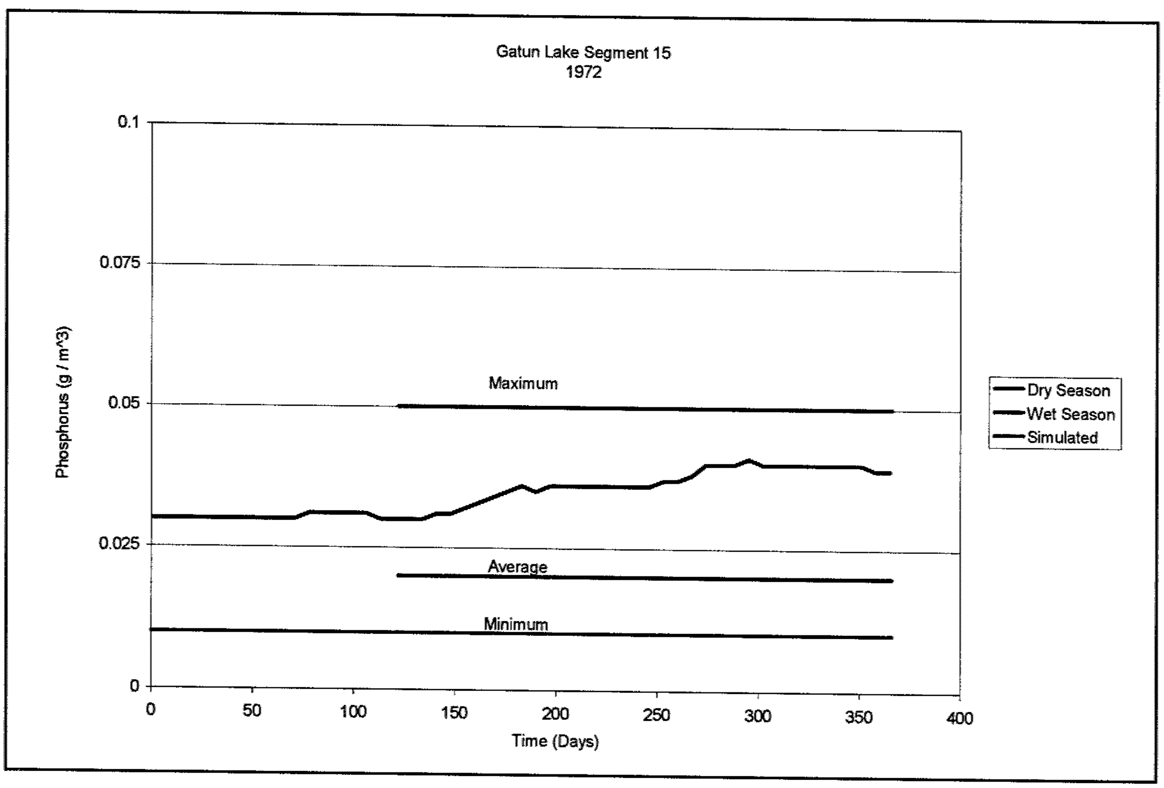

Figure 6-45. 1972 calibration phosphorus, segment 15

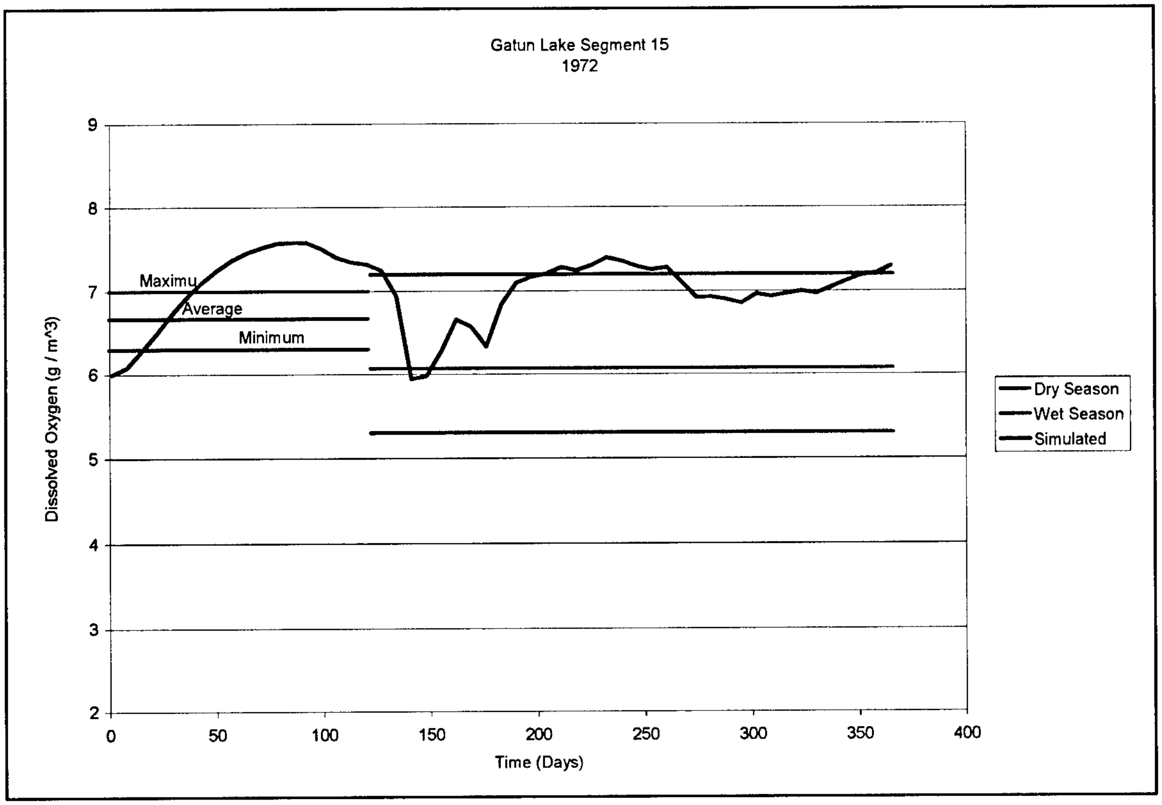

Figure 6-46. 1972 calibration dissolved oxygen, segment 15

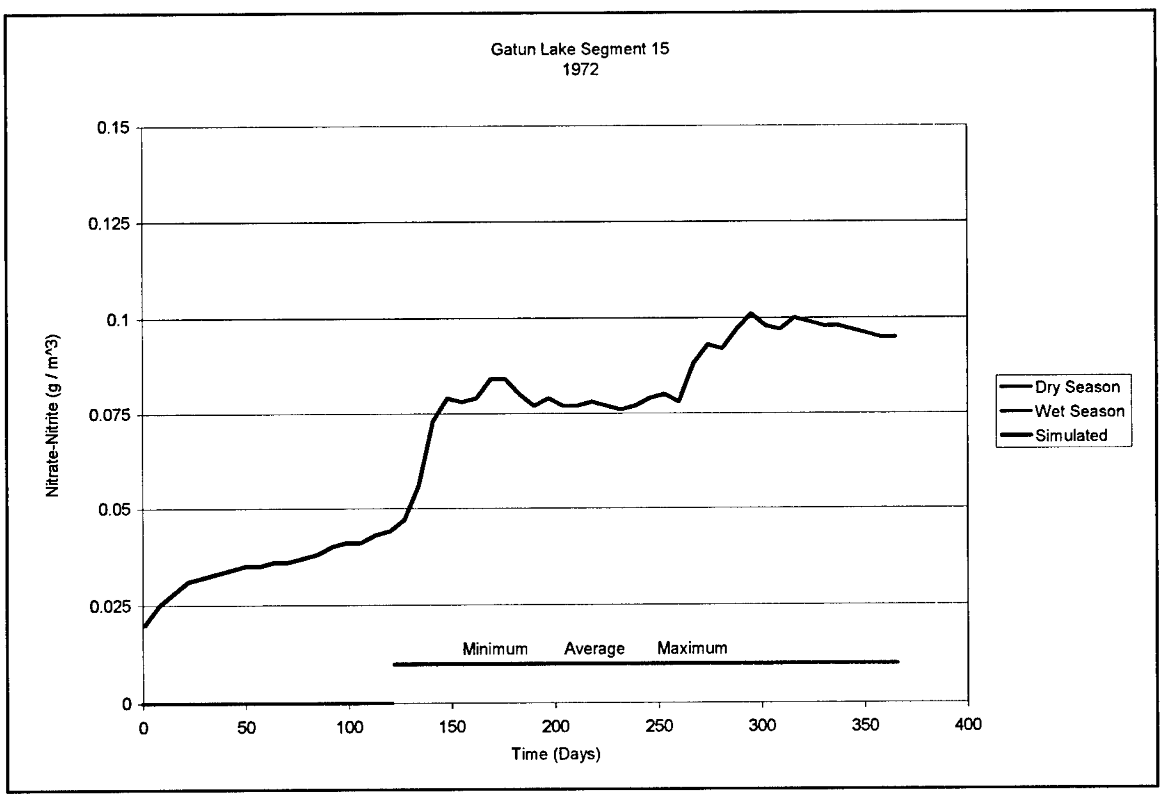

Figure 6-47. 1972 calibration nitrite-nitrate, segement 15

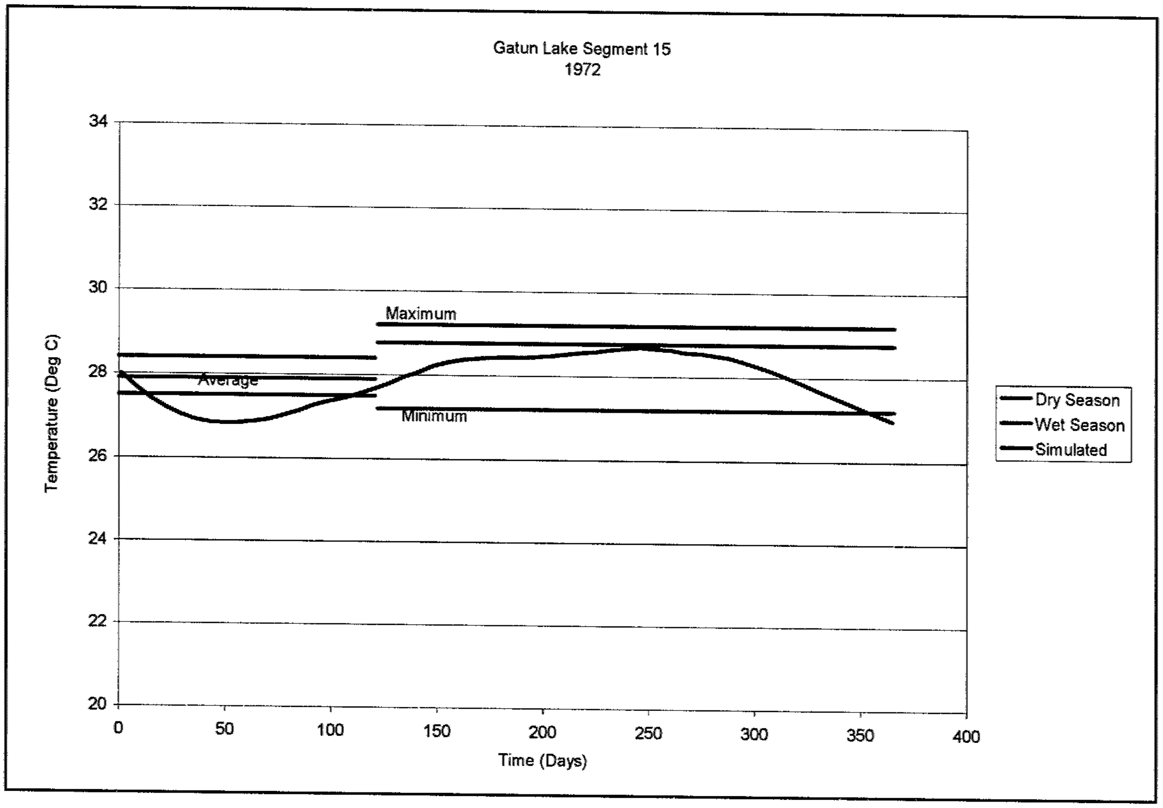

Figure 6-48. 1972 calibration temperature, segment 15

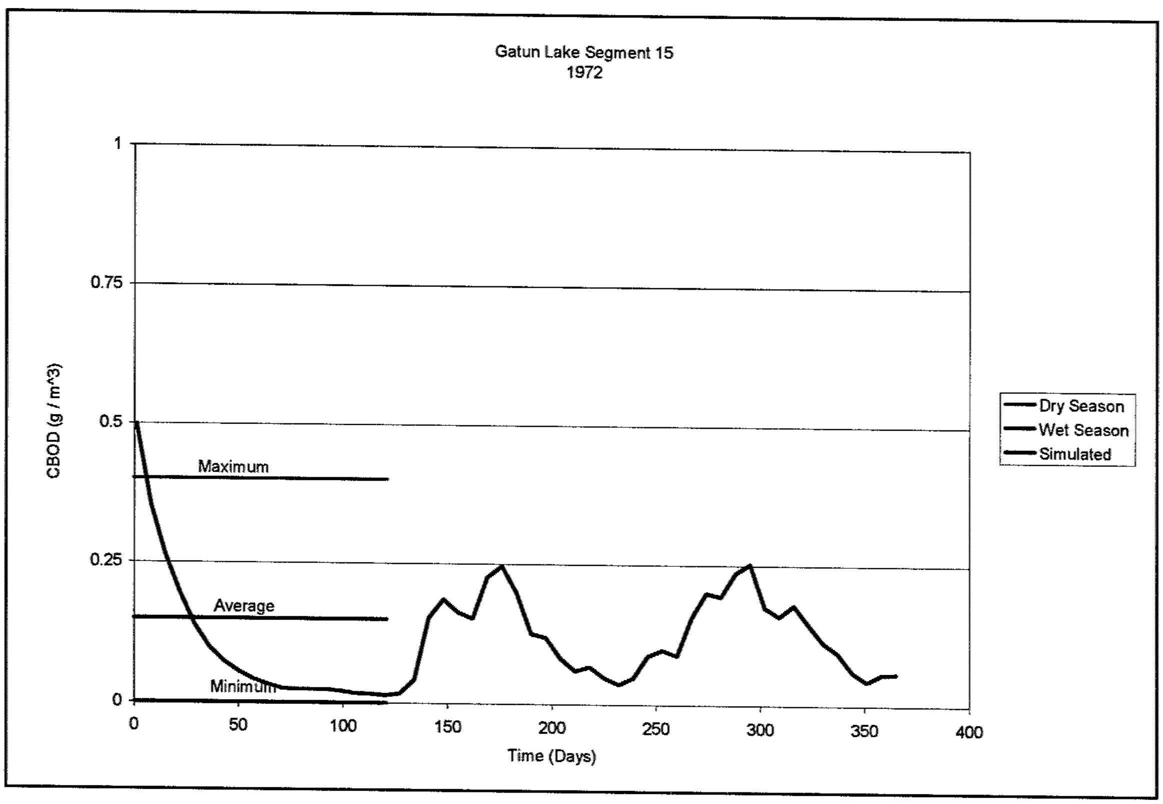

Figure 6-49. 1972 calibration CBOD, segment 15

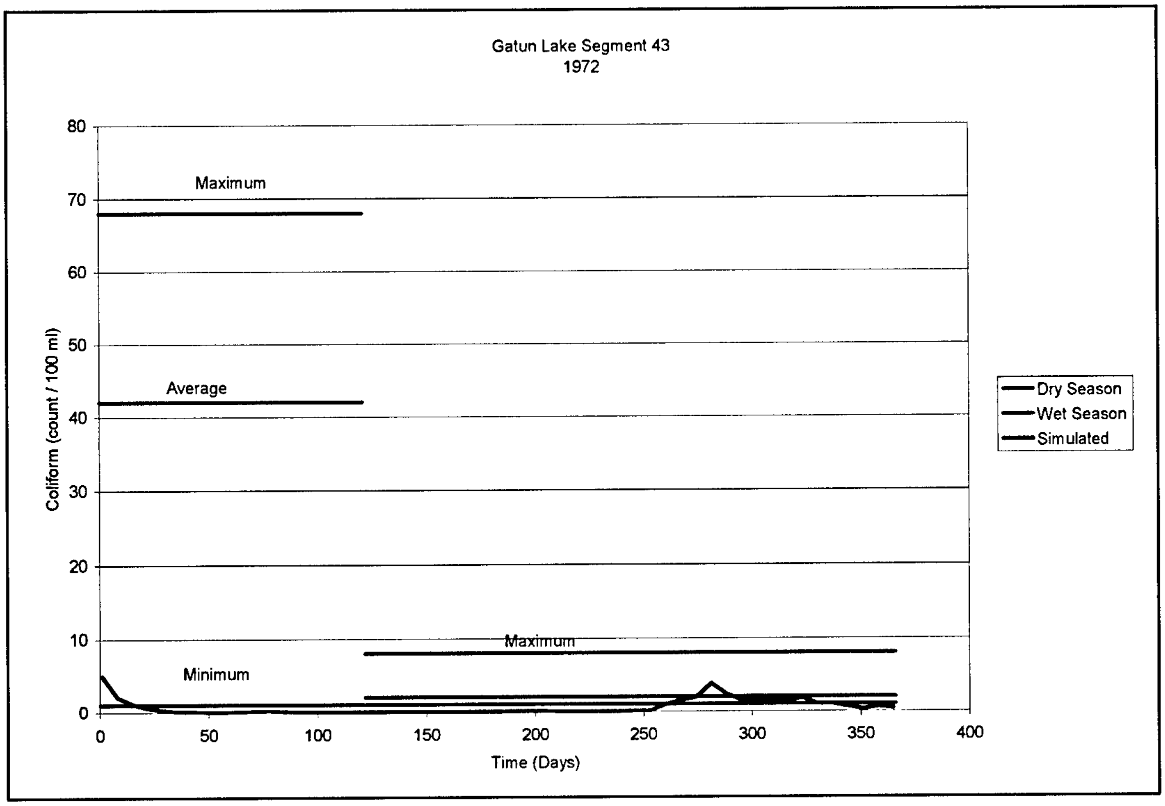

Figure 6-50. 1972 calibration coliform, segment 43

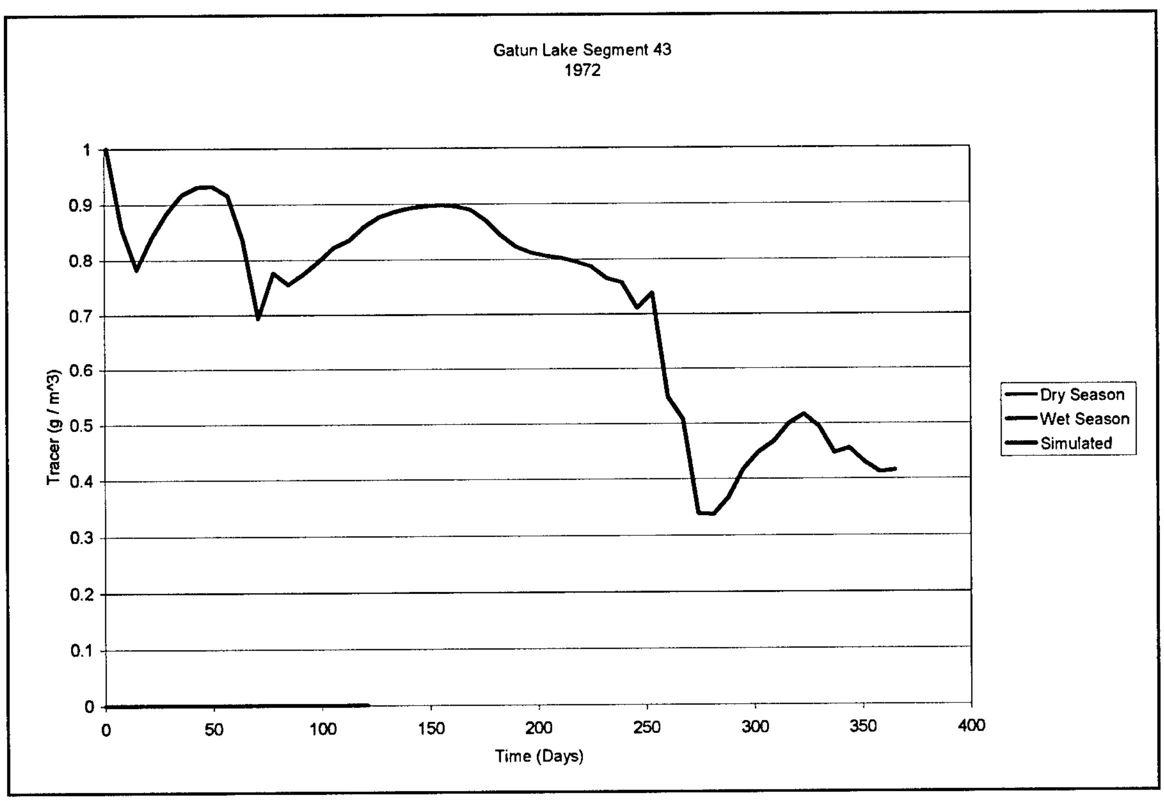

Figure 6-51. 1972 calibration tracer, segment 43

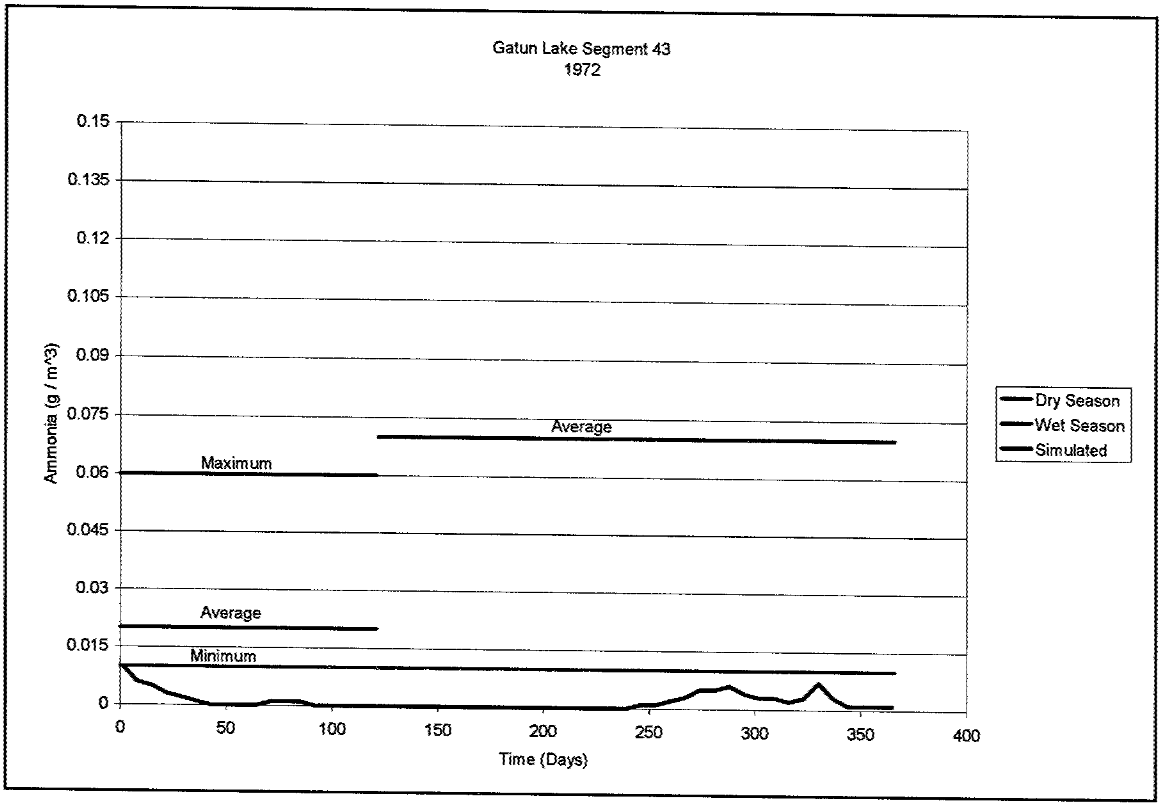

Figure 6-52. 1972 calibration ammonia, segment 43

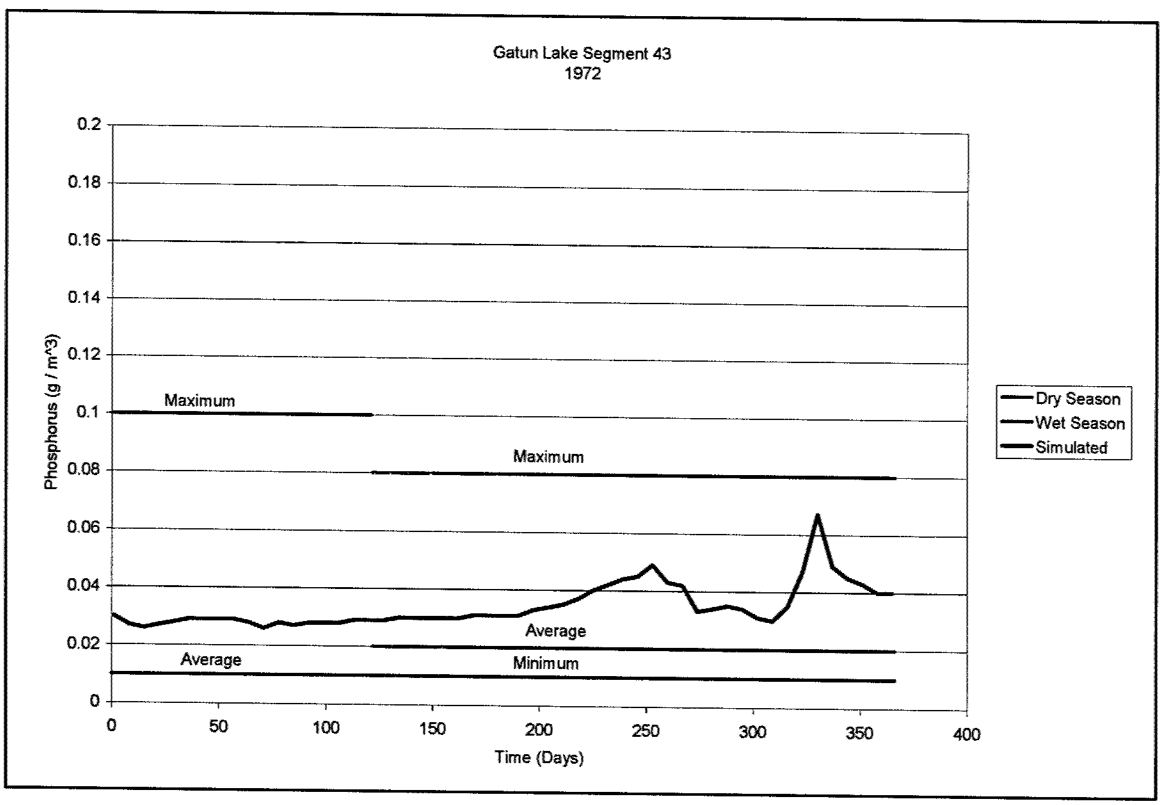

Figure 6-53. 1972 calibration phosphorus, segment 43

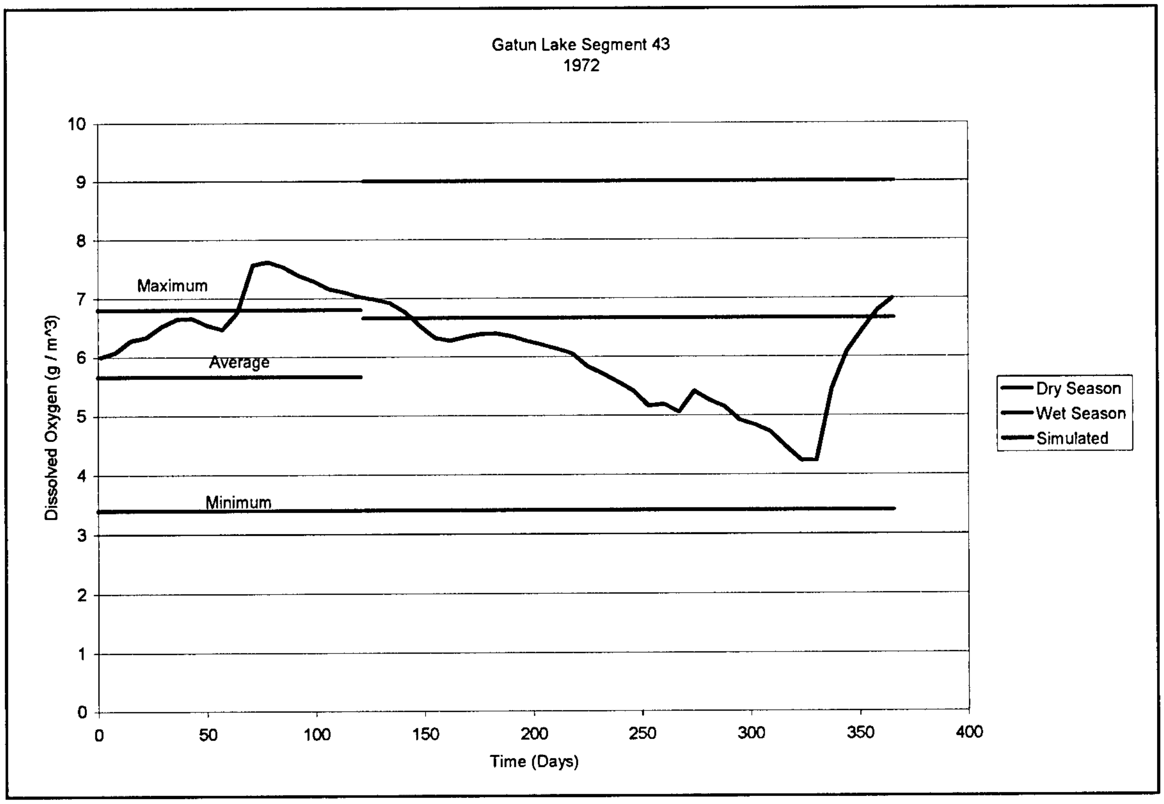

Figure 6-54. 1972 calibration dissolved oxygen, segment 43

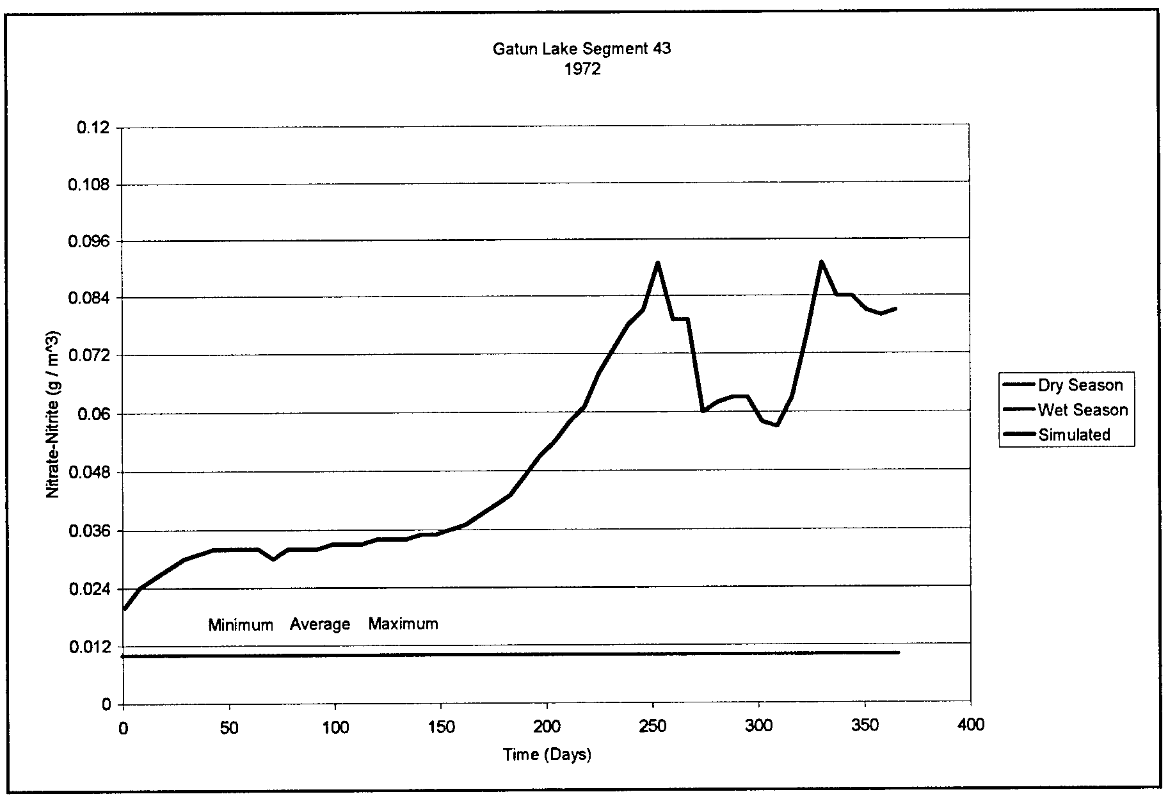

Figure 6-55. 1972 calibration nitrate-nitrite, segment 43

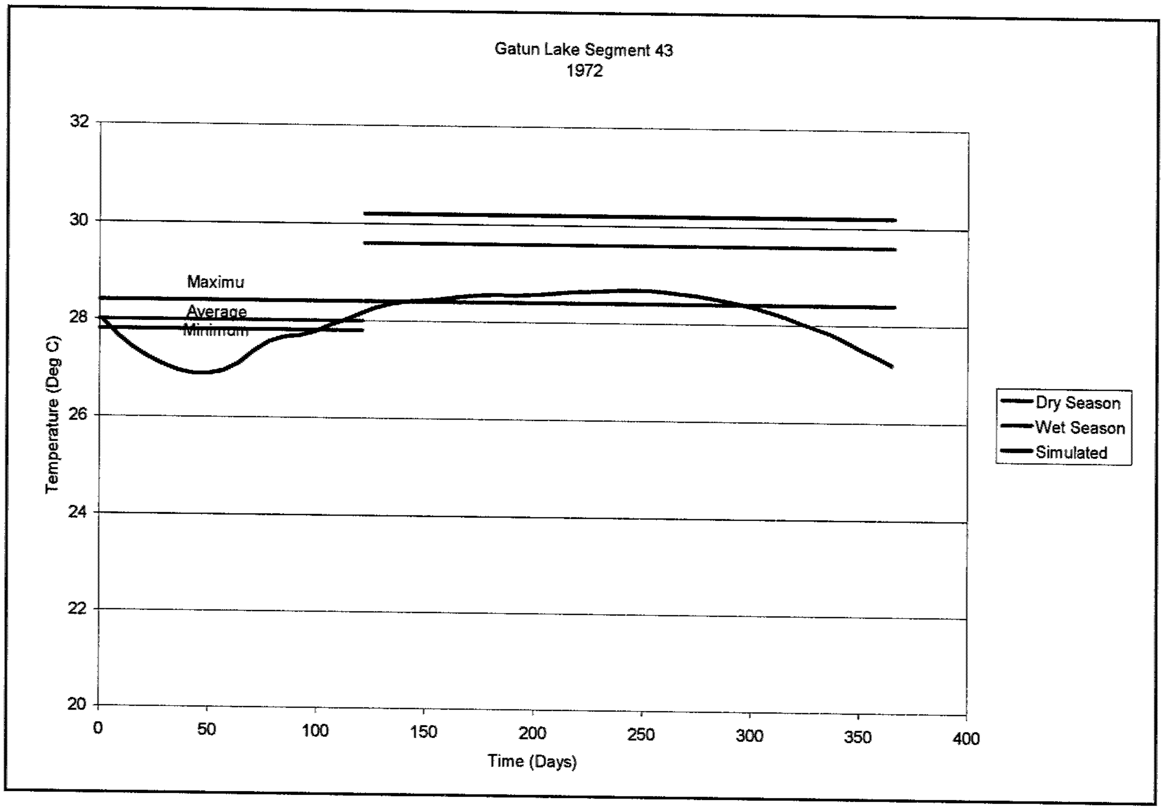

Figure 6-56. 1972 calibration temperature, segment 43

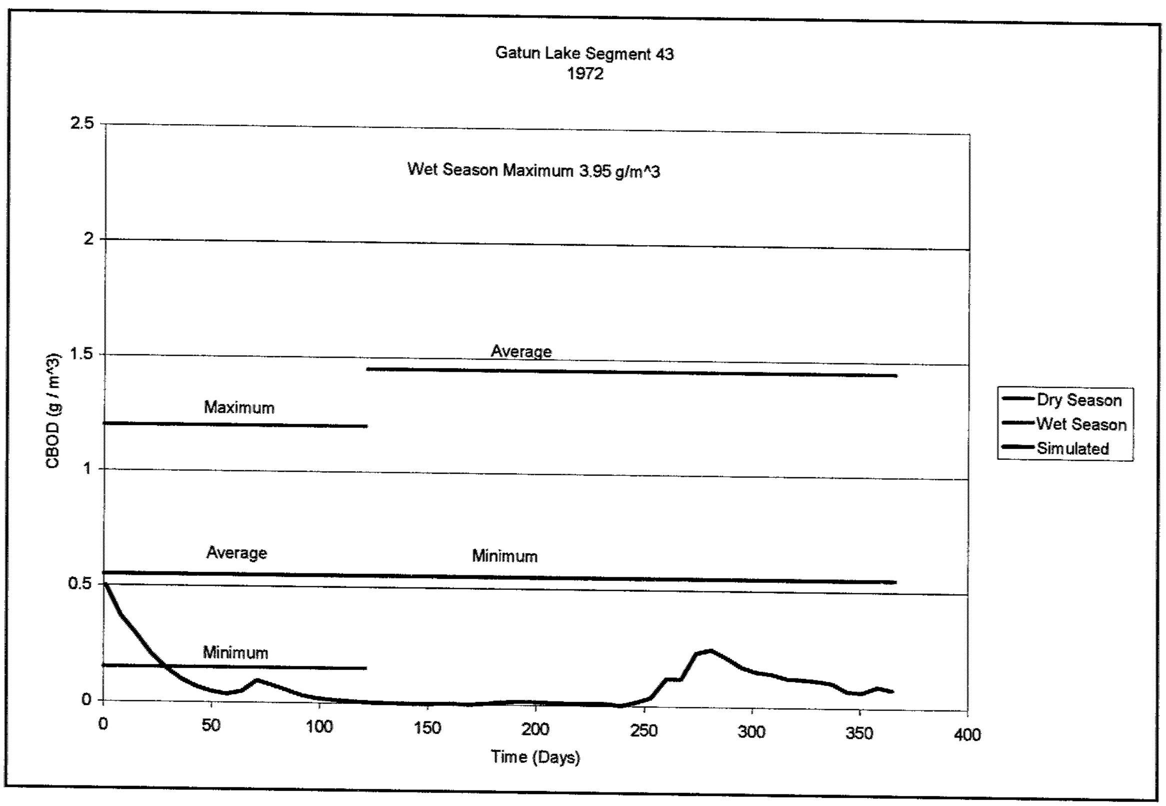

Figure 6-57. 1972 calibration CBOD, segment 43

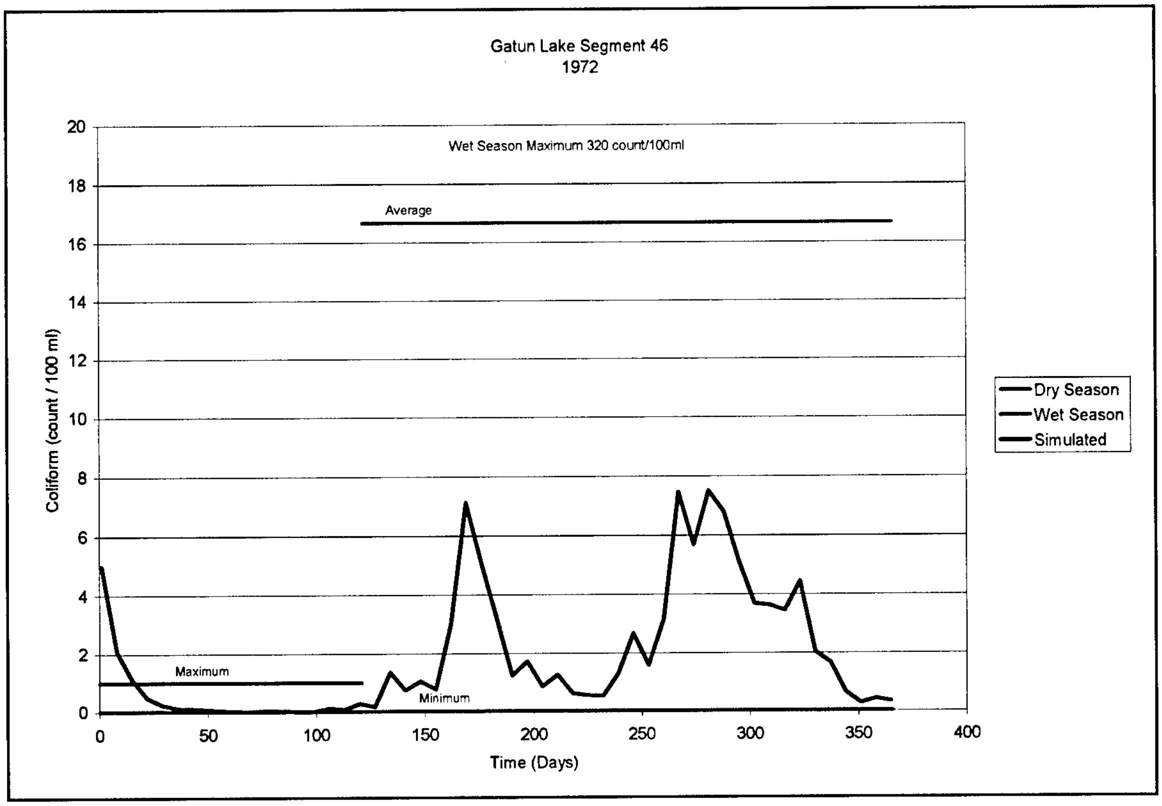

Figure 6-58. 1972 calibration coliform, segment 46

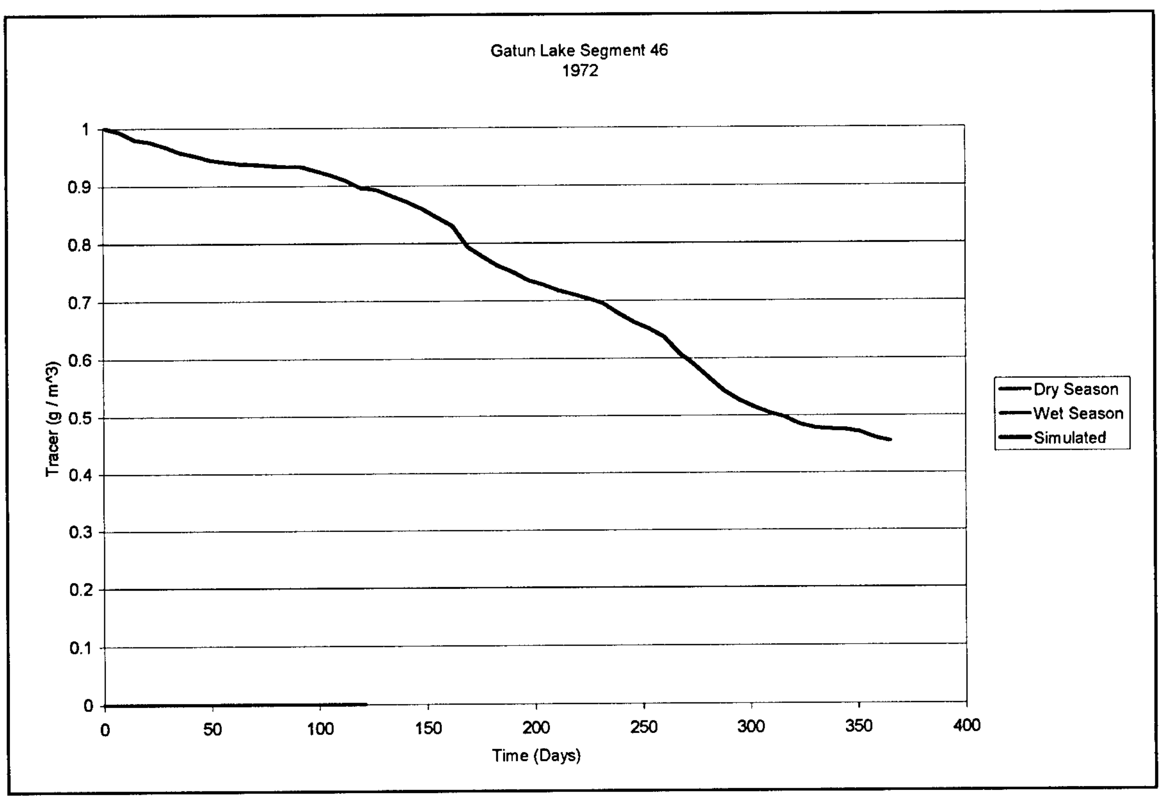

Figure 6-59. 1972 calibration tracer, segment 46

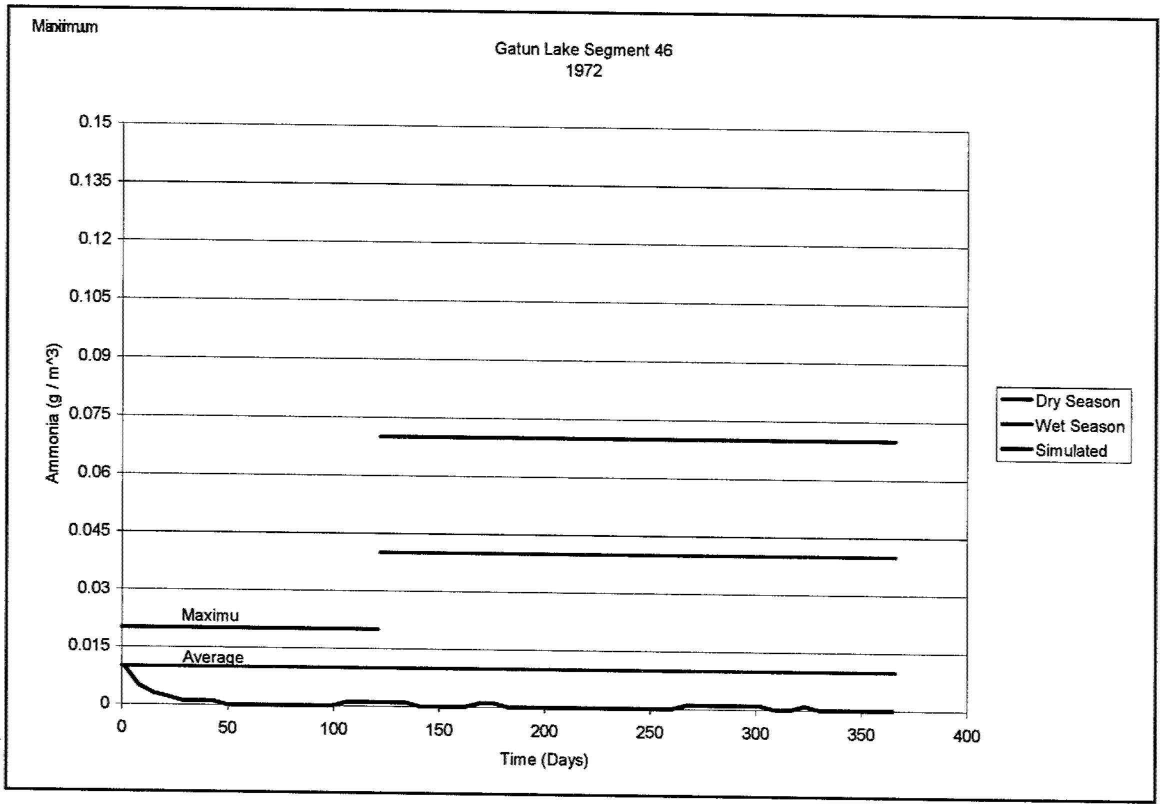

Figure 6-60. 1972 calibration ammonia, segment 46

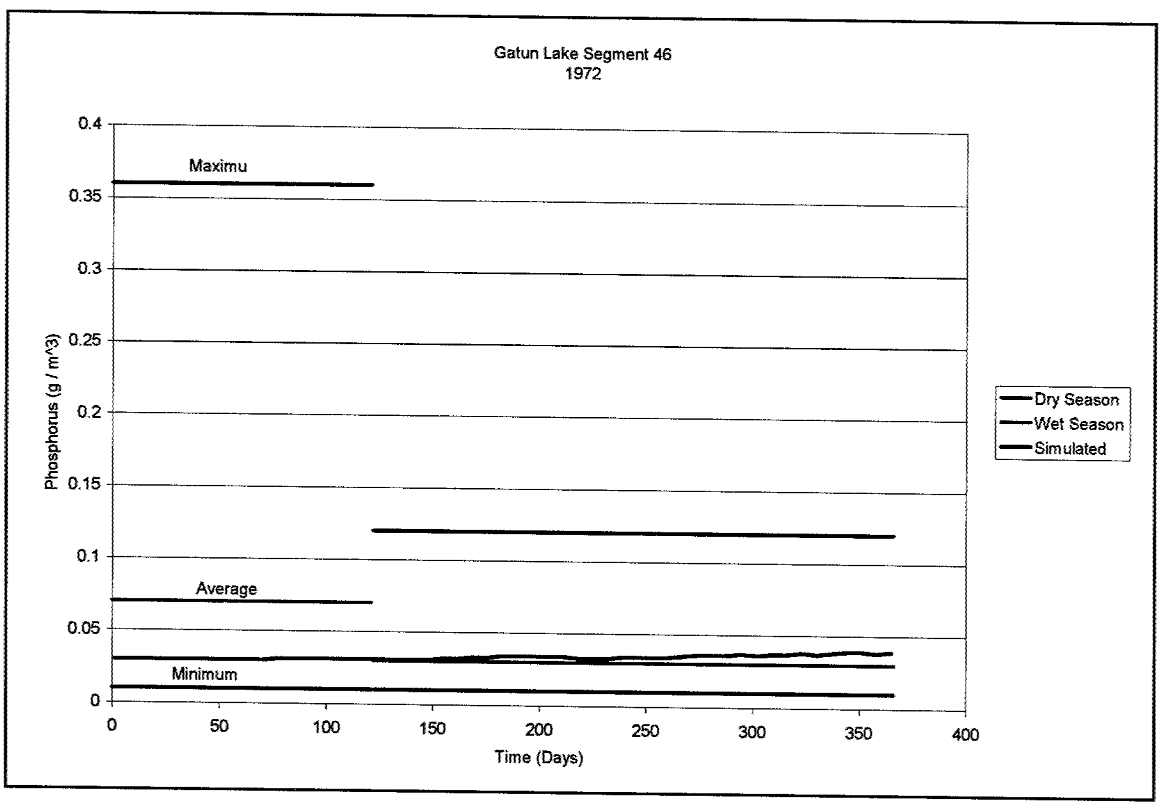

Figure 6-61. 1972 calibration phosphorus, segment 46

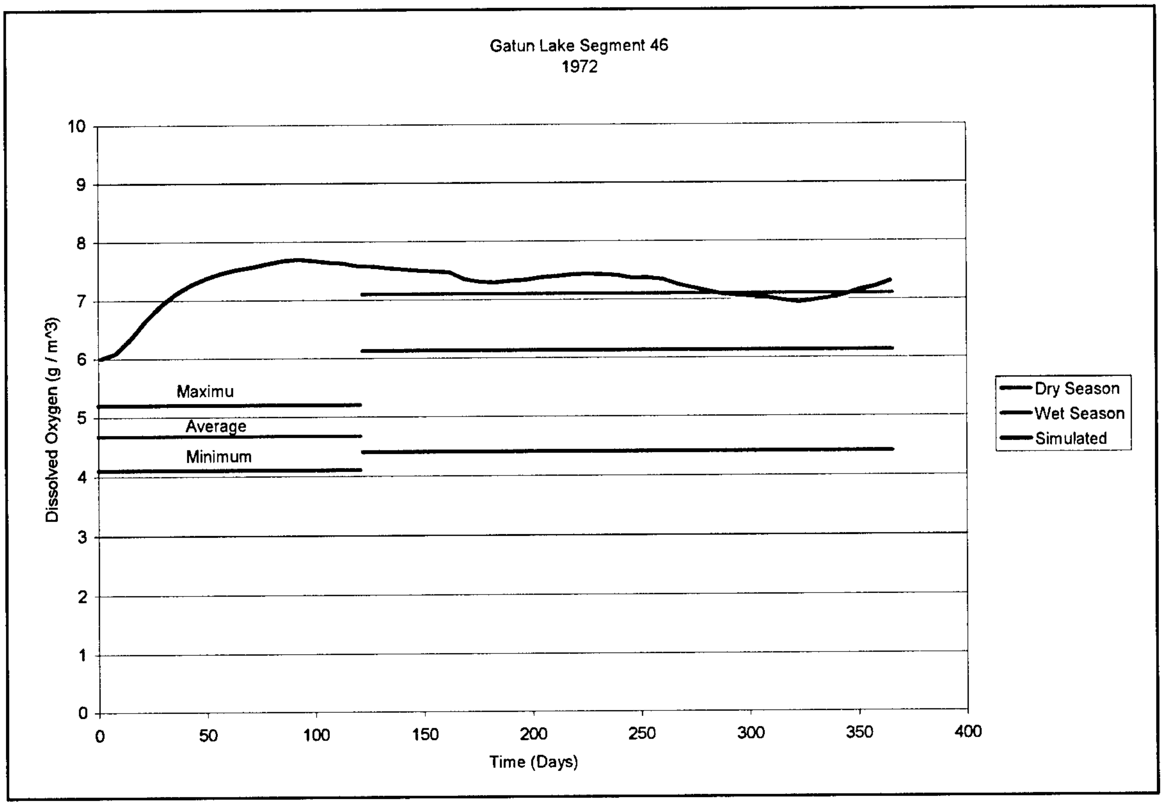

Figure 6-62. 1972 calibration dissolved oxygen, segment 46

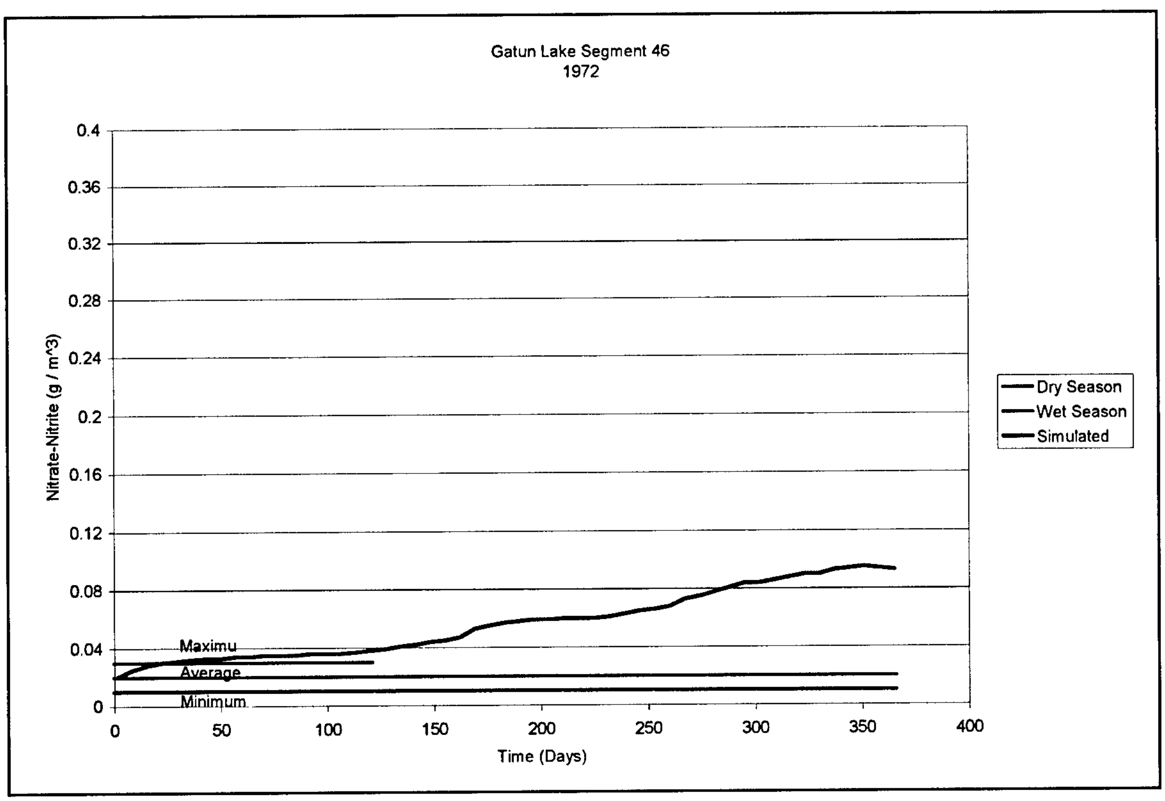

Figure 6-63. 1972 calibration nitrite-nitrate, segment 46

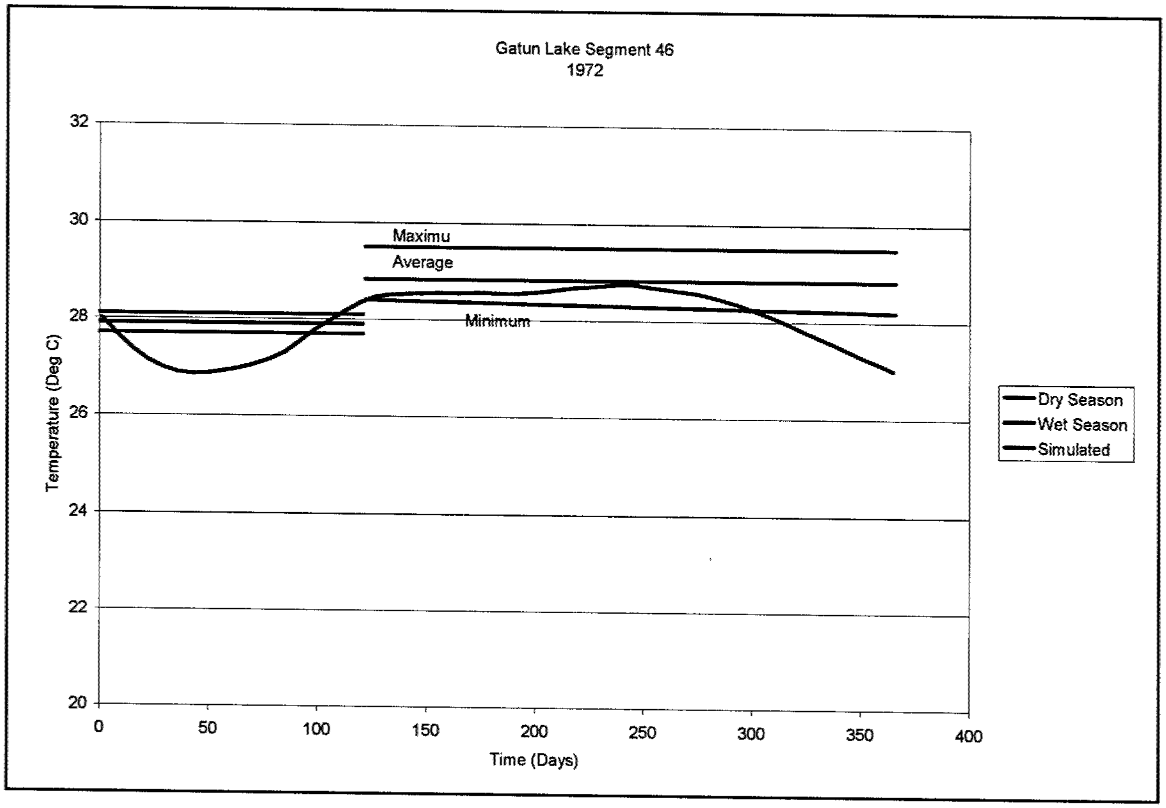

Figure 6-64. 1972 calibration temperature, segment 46

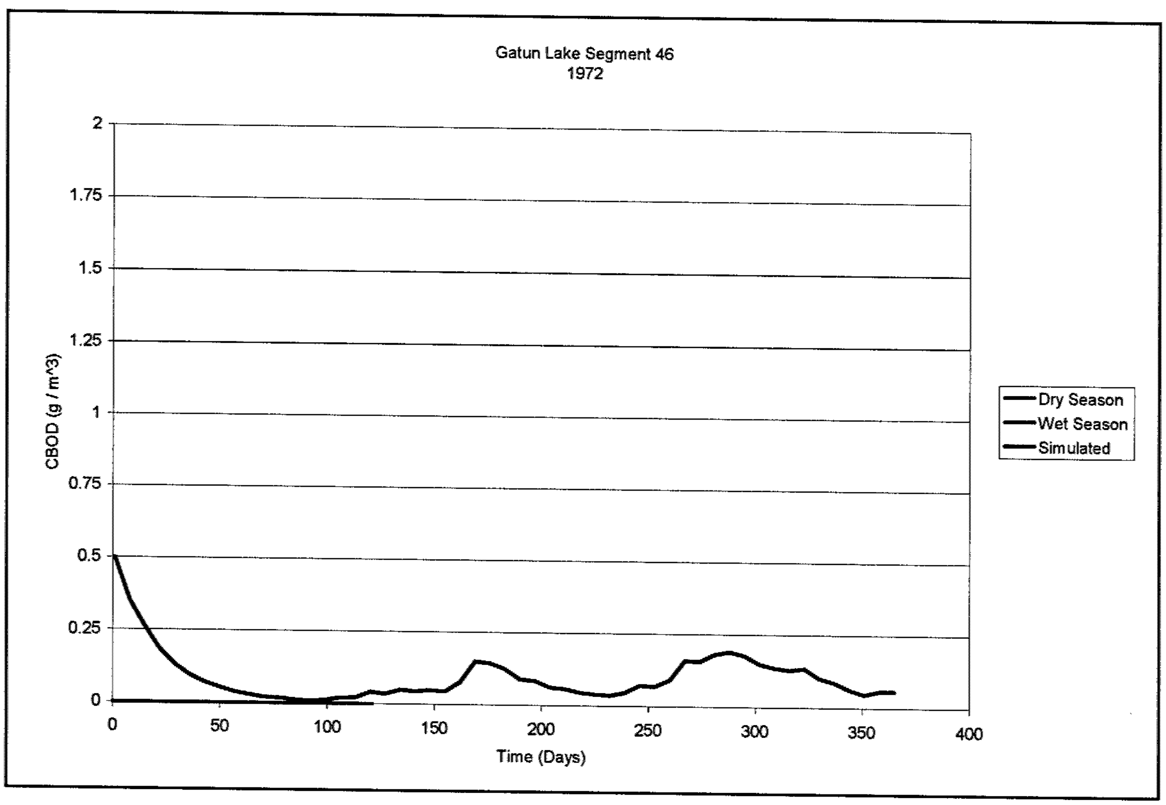

Figure 6-65. 1972 calibration CBOD, segment 46

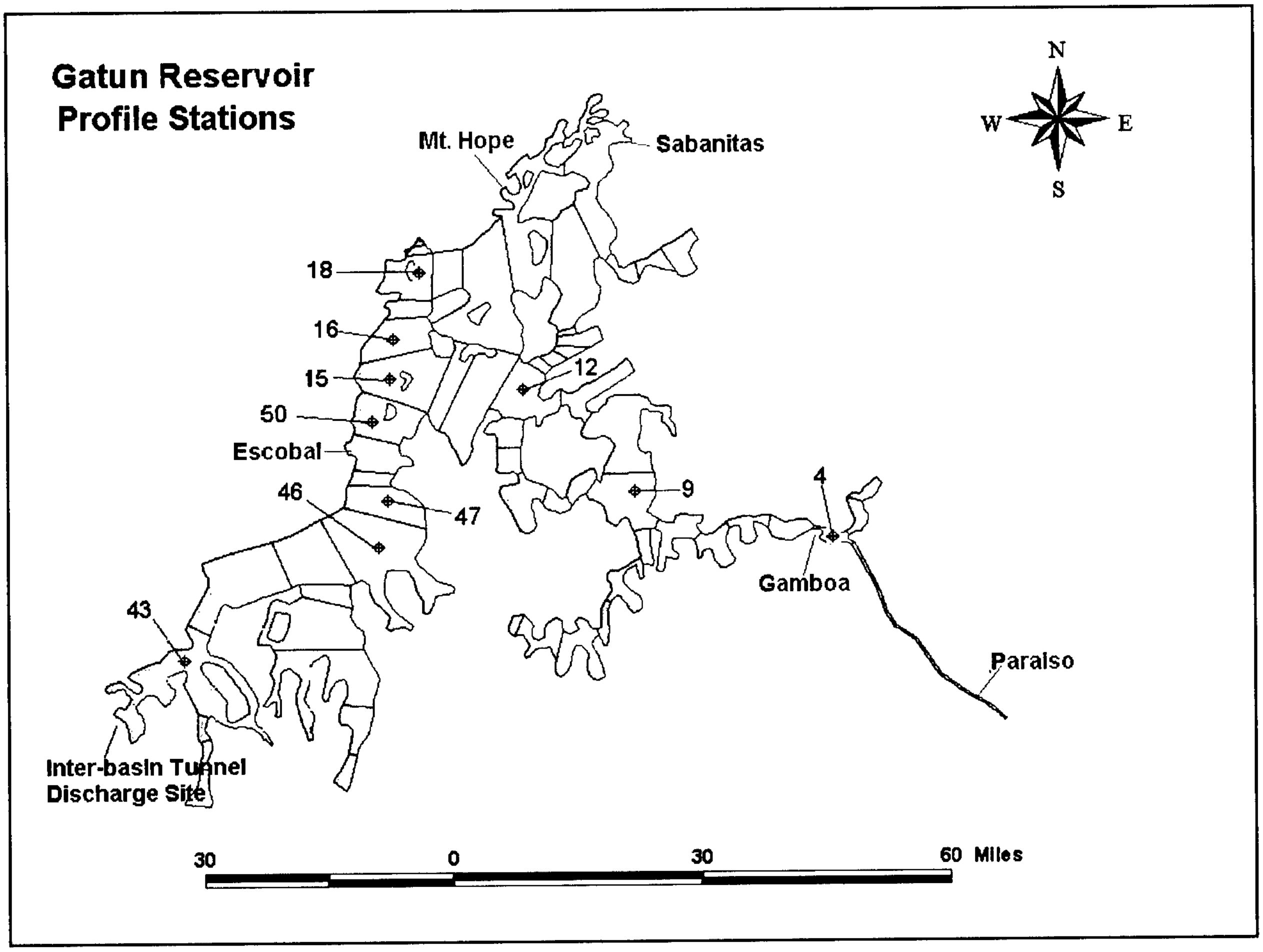

Figure 6-66. Gatun profile stations

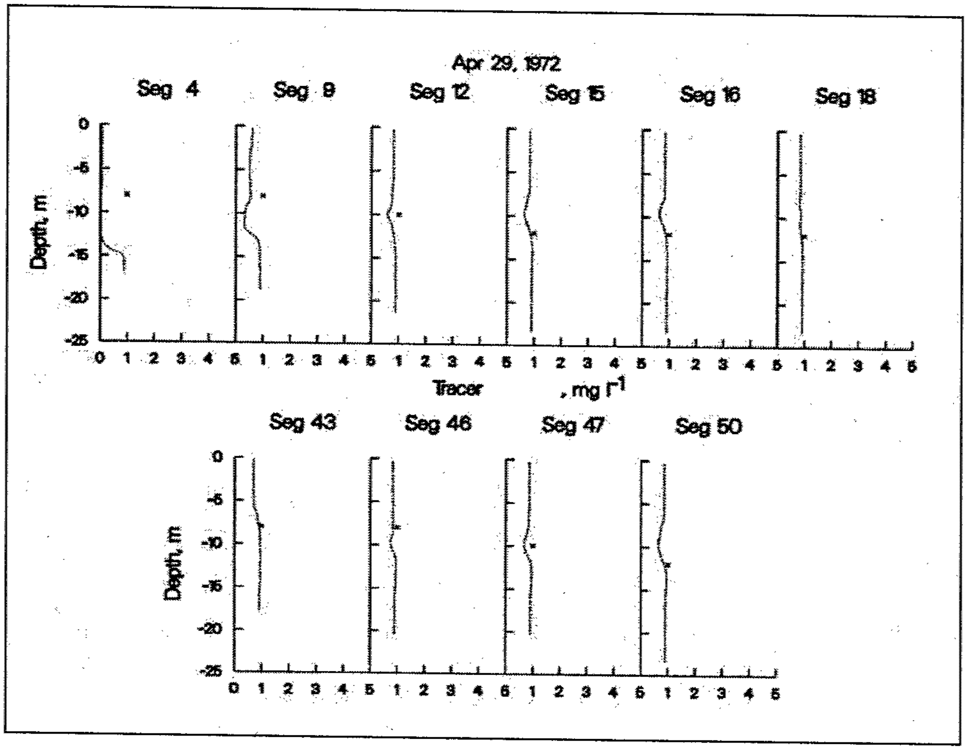

Figure 6-67. Average conditions calibration profile tracer

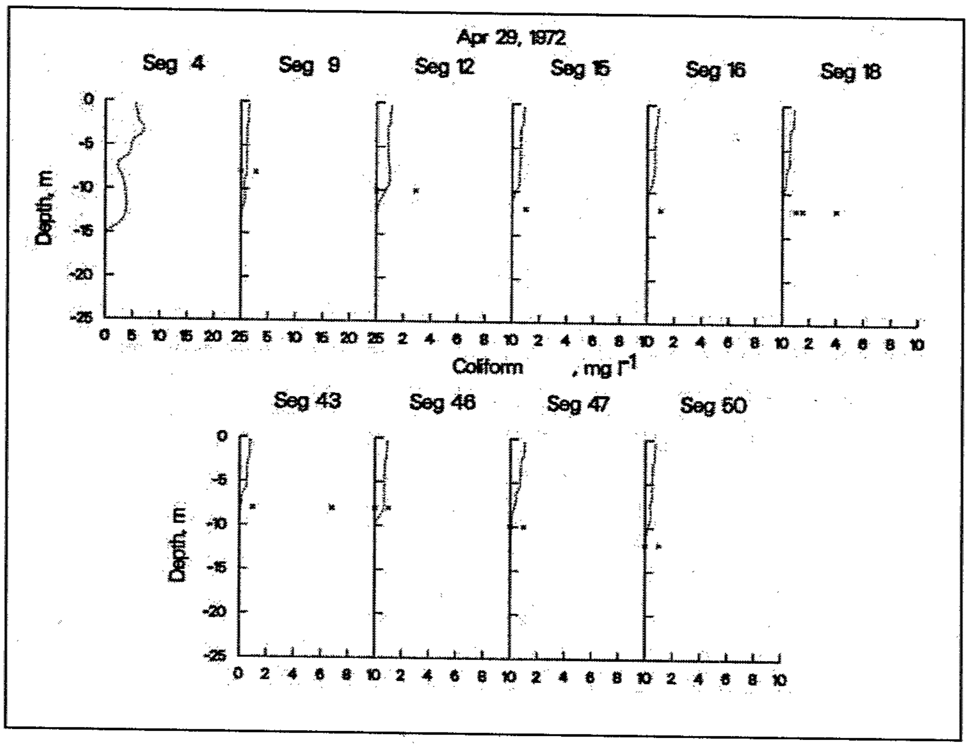

Figure 6-68. Average conditions calibration profile coliform

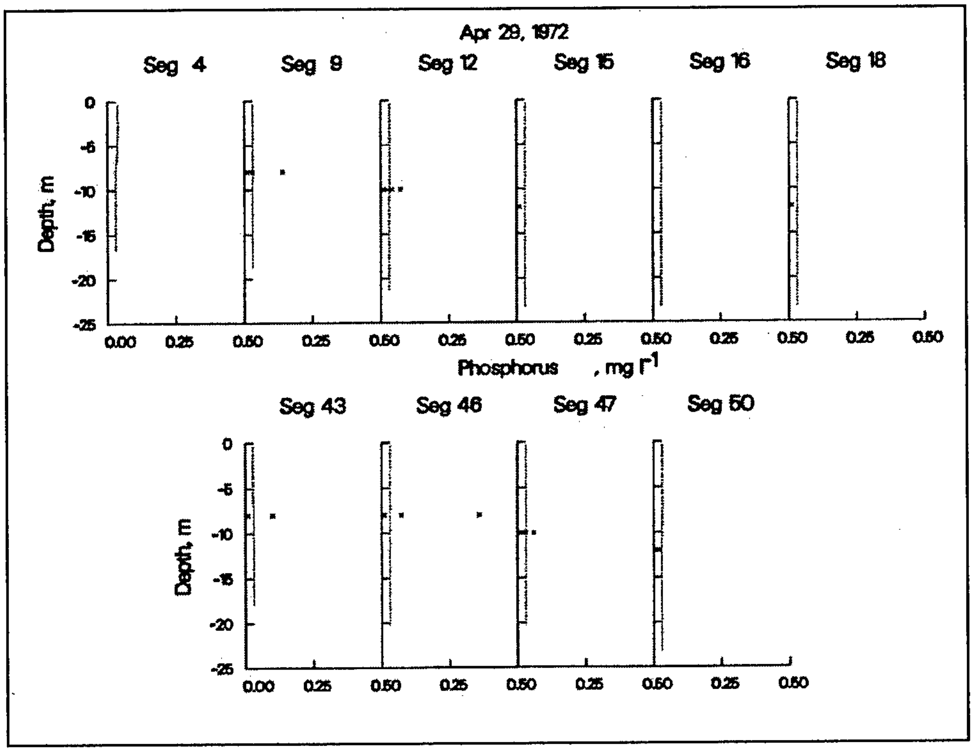

Figure 6-69. Average conditions calibration profile phosphorus

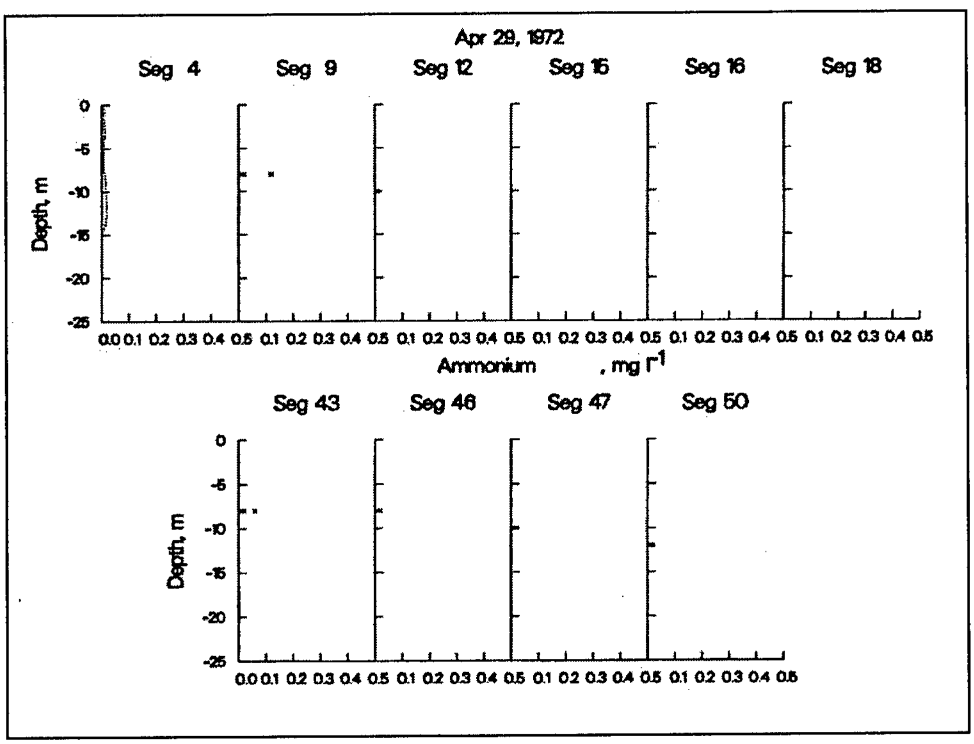

Figure 6-70. Average conditions calibration profile ammonium

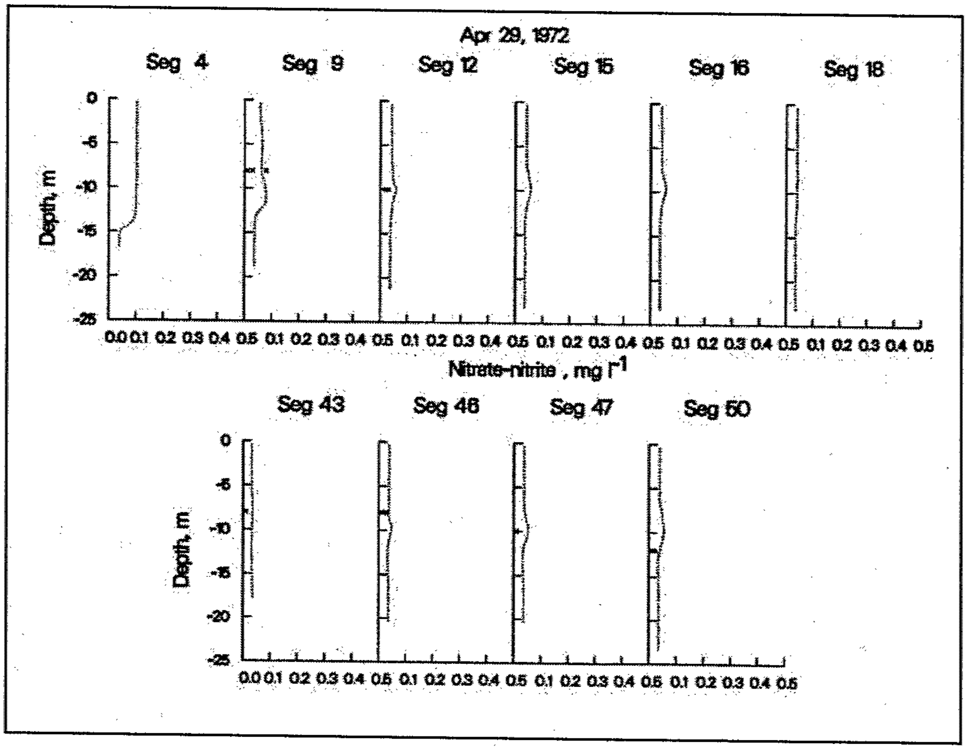

Figure 6-71. Average conditions calibration profile nitrate-nitrite

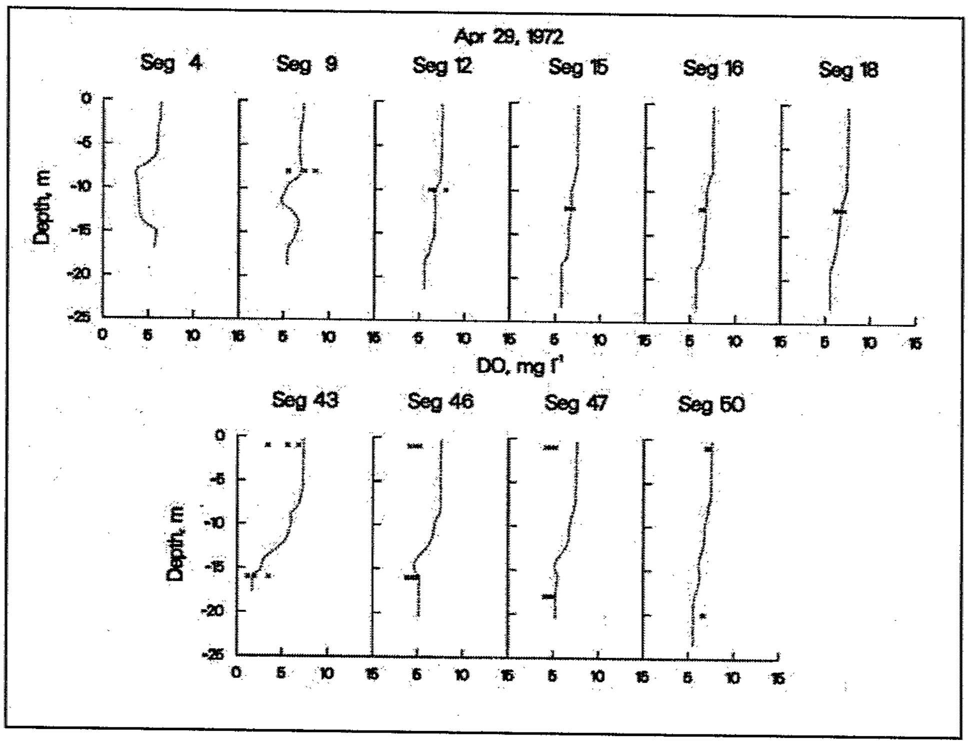

Figure 6-72. Average conditions calibration profile dissolved oxygen

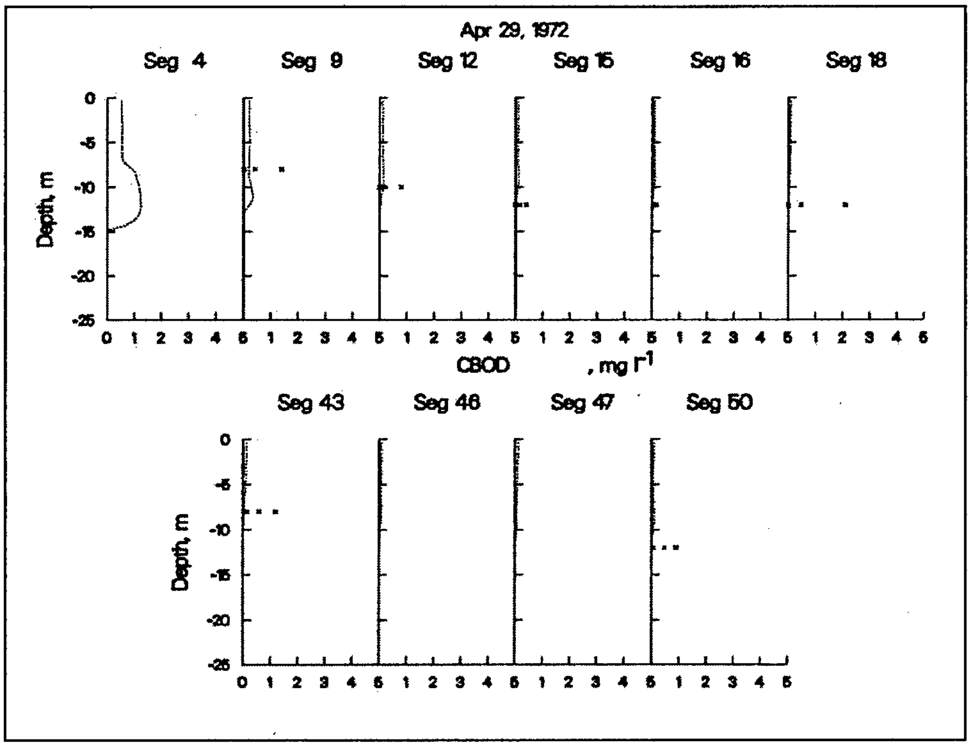

Figure 6-73. Average conditions calibration profile CBOD

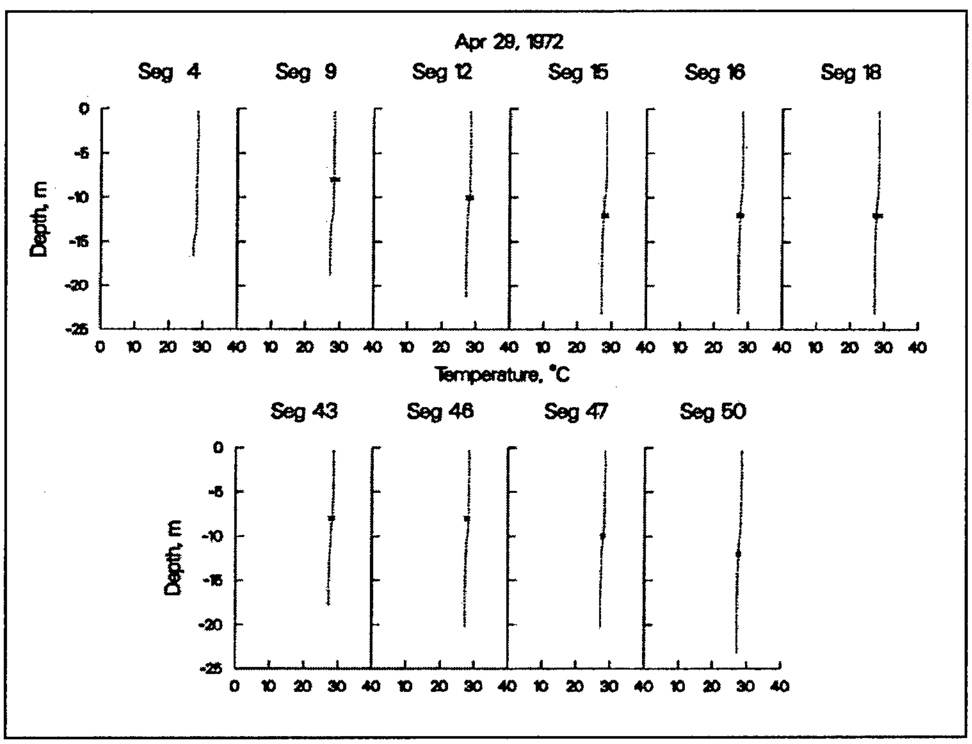

Figure 6-74. Average conditions calibration profile temperature

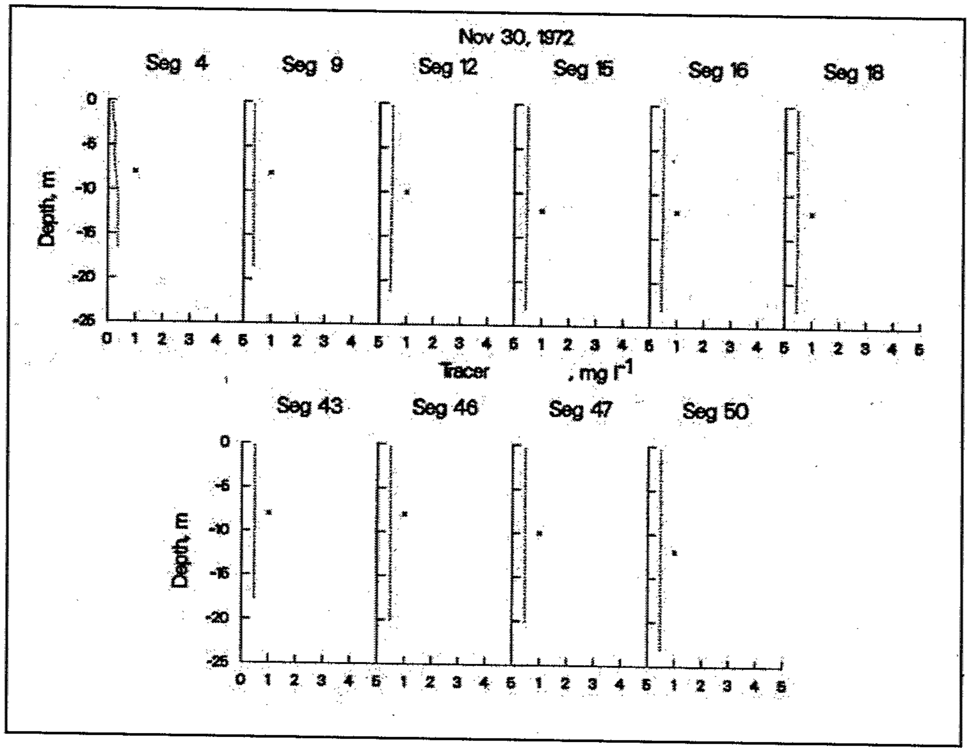

Figure 6-75. Average conditions calibration profile tracer

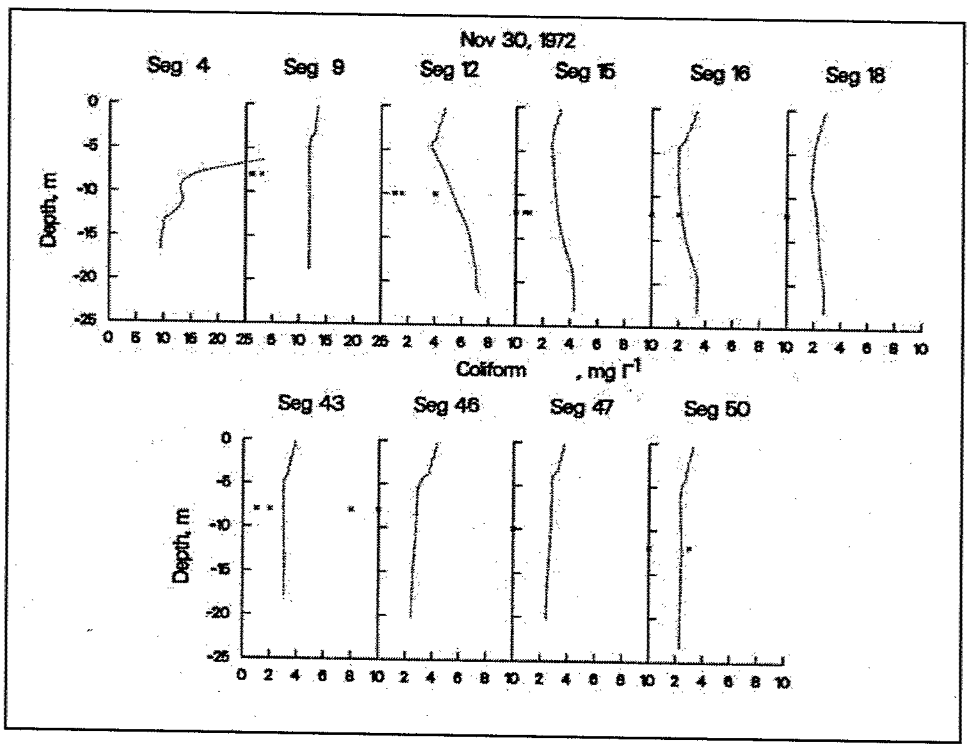

Figure 6-76. Average conditions calibration profile coliform

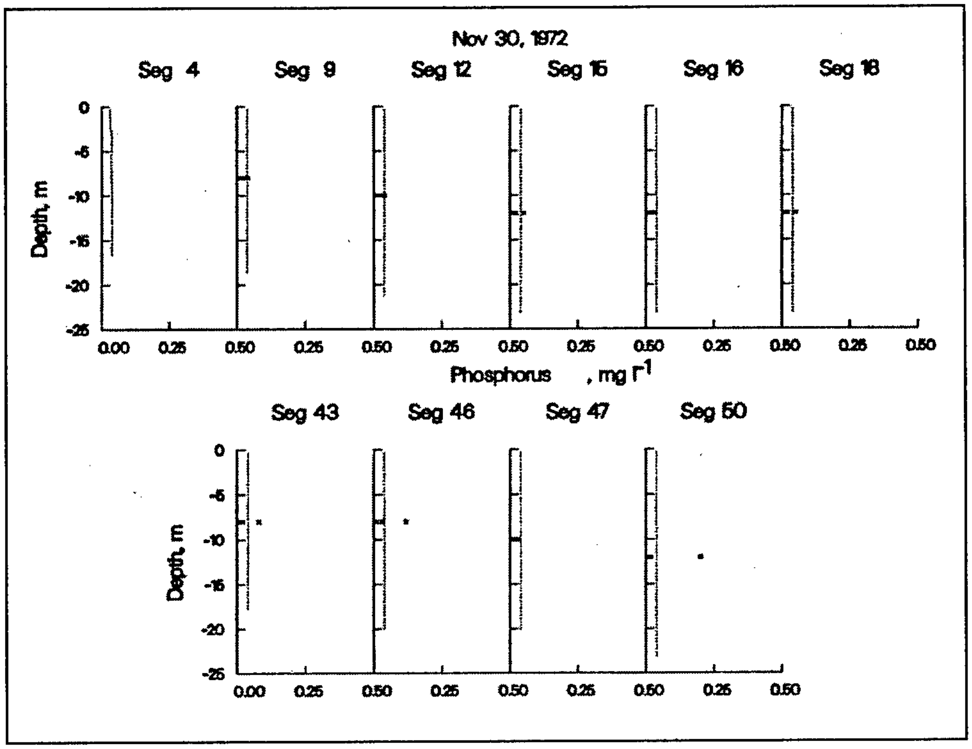

Figure 6-77. Average conditions calibration profile phosphorus

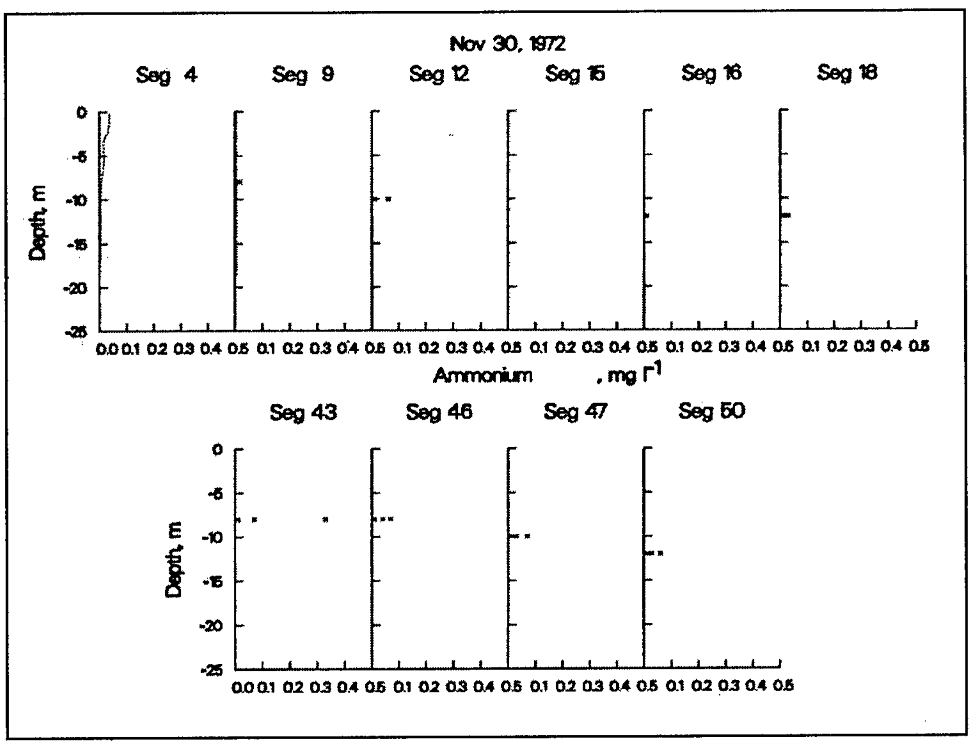

Figure 6-78. Average conditions calibration profile ammonium

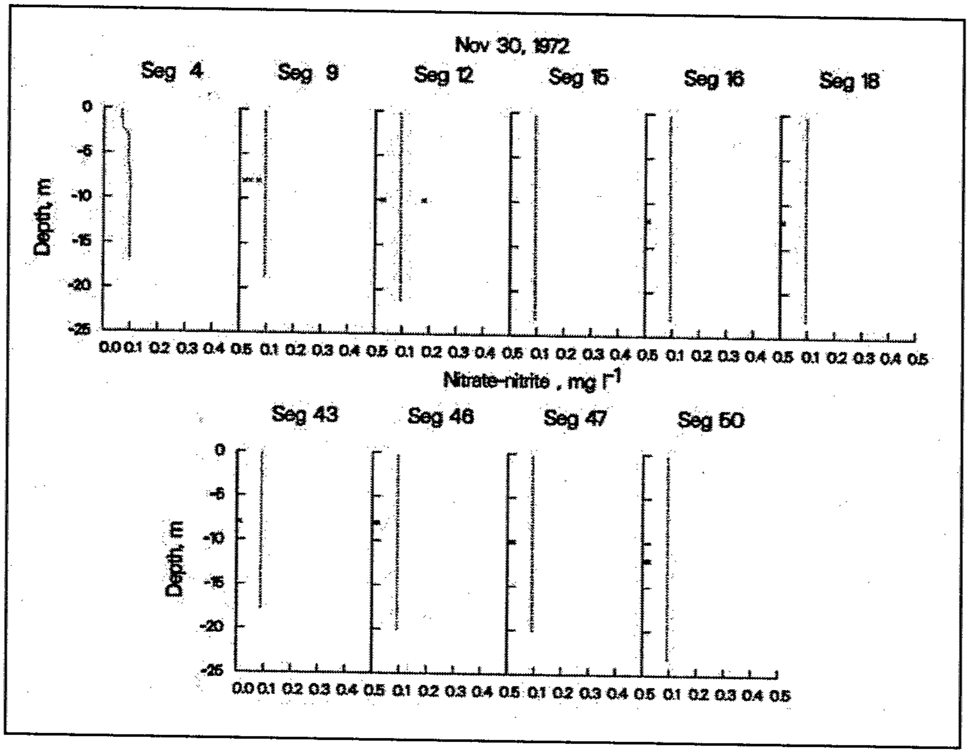

Figure 6-79. Average conditions calibration profile nitrate-nitrite

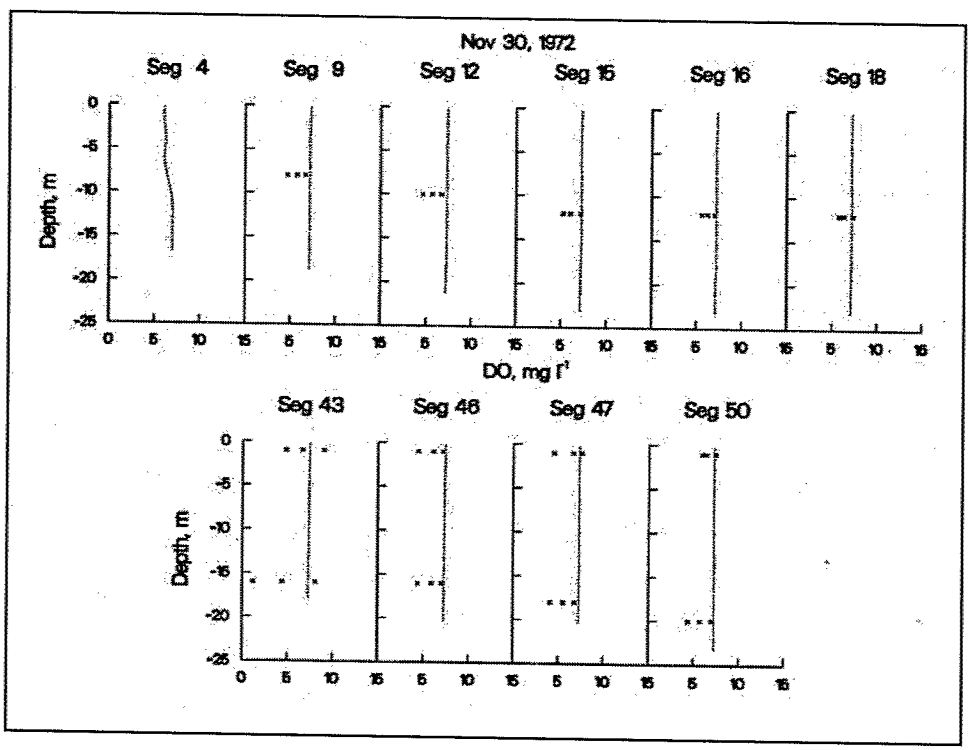

Figure 6-80. Average conditions calibration profile dissolved oxygen

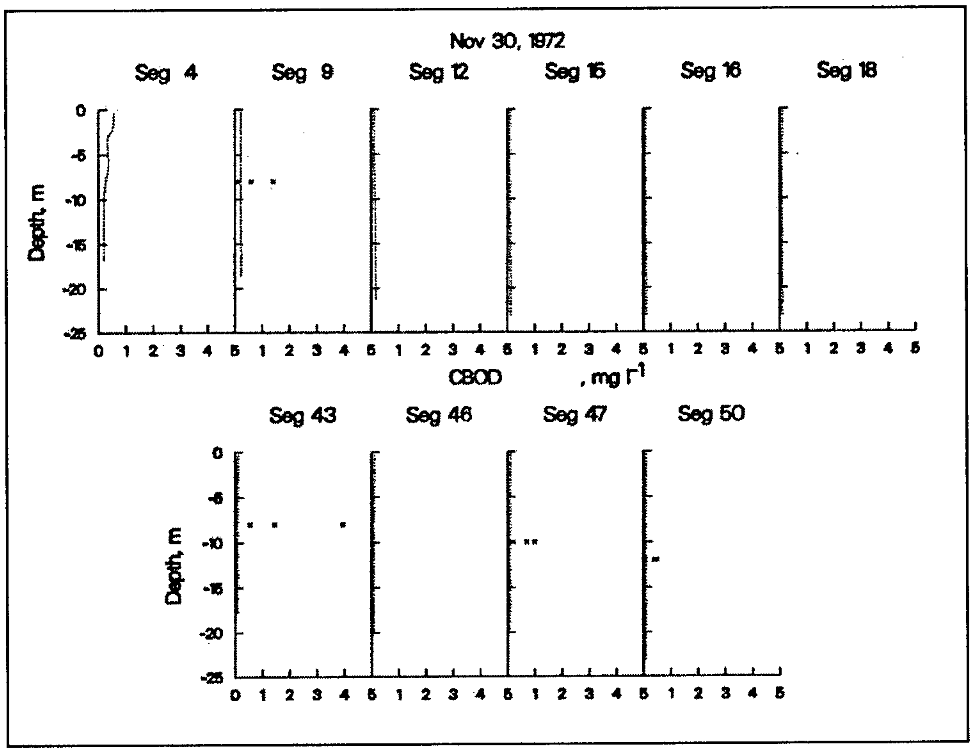

Figure 6-81. Average conditions calibration profile CBOD

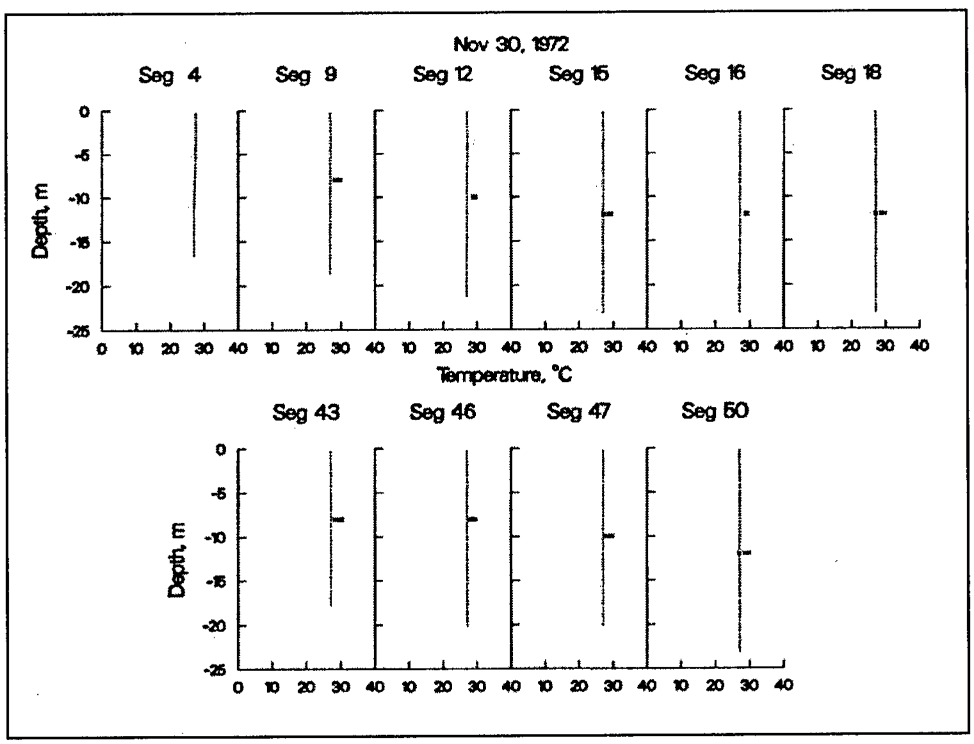

Figure 6-82. Aaverage conditions calibration profile temperature

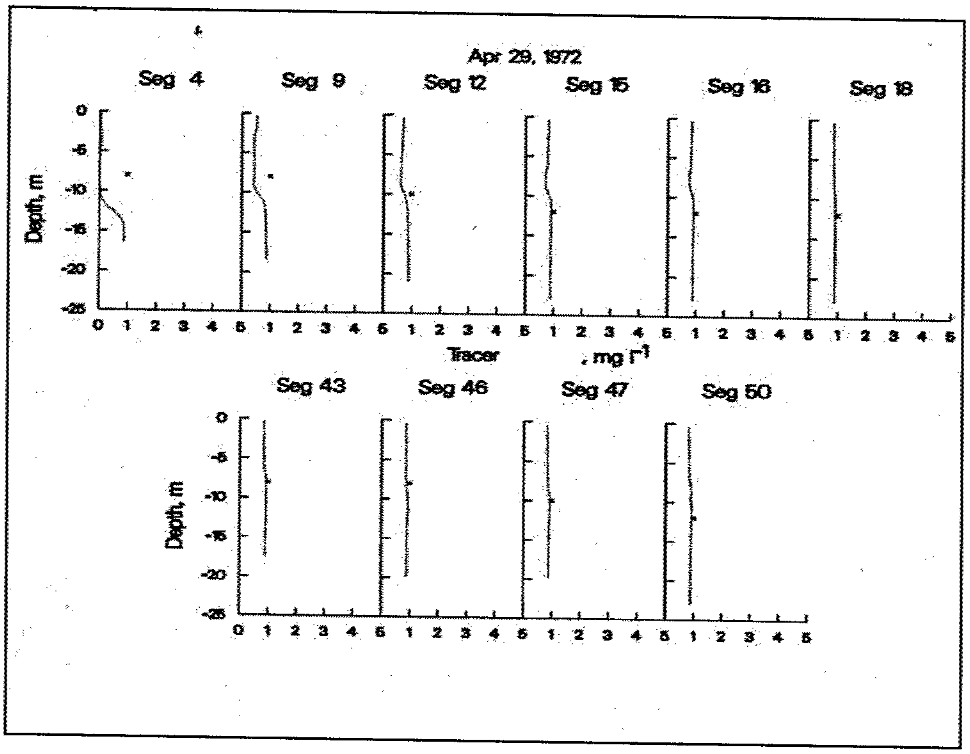

Figure 6-83. 1972 calibration profile tracer

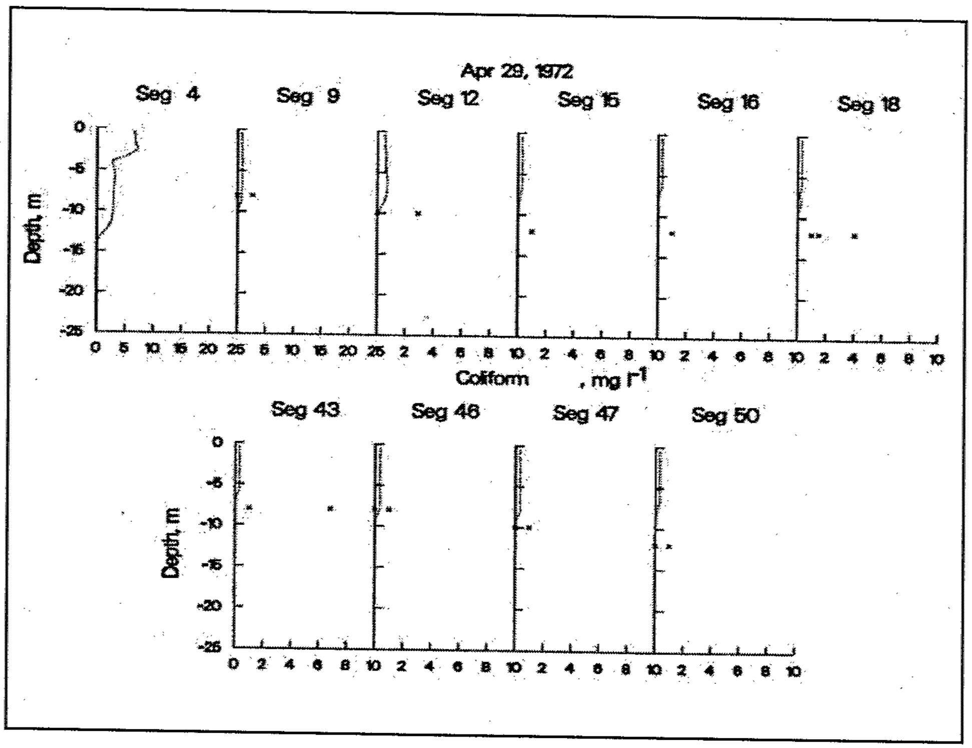

Figure 6-84. 1972 calibration profile coliform

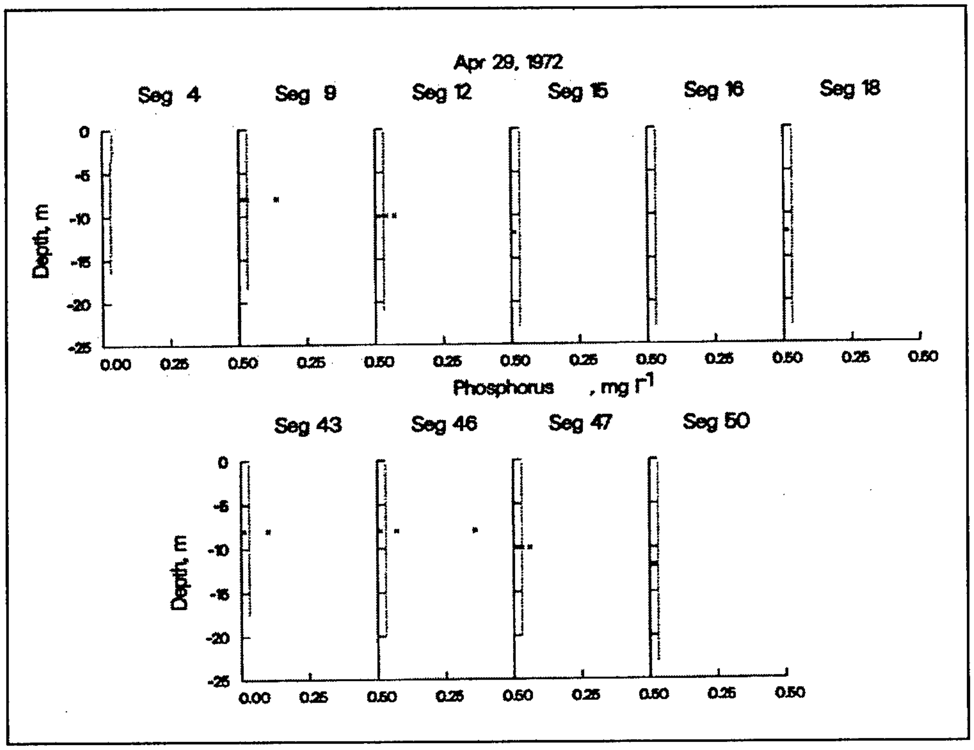

Figure 6-85. 1972 calibration profile phosphorus

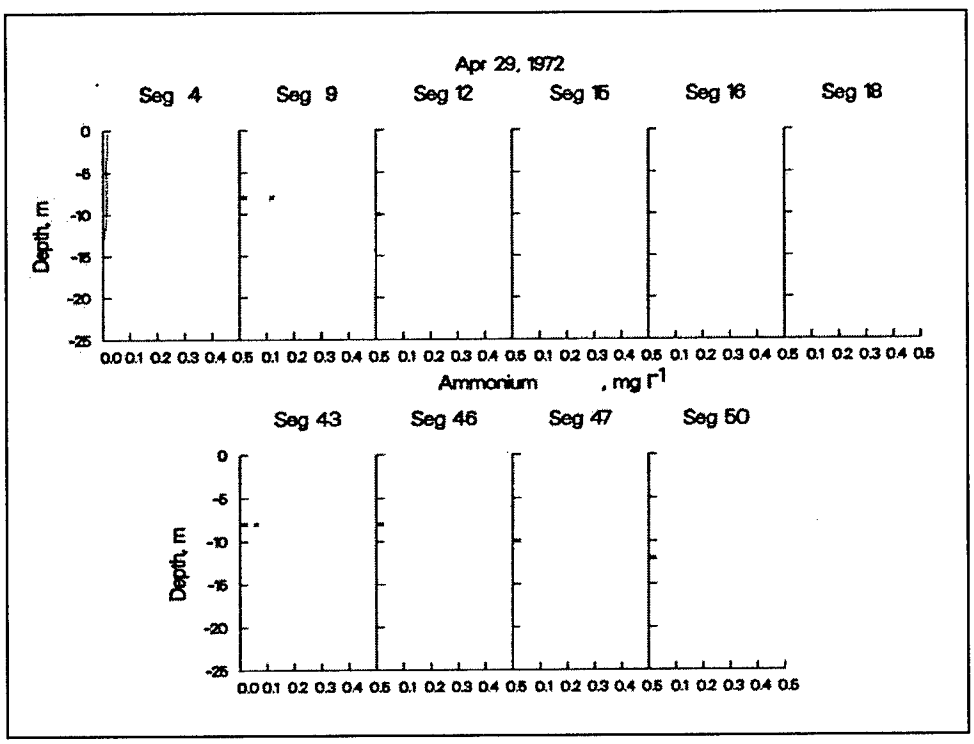

Figure 6-86. 1972 calibration profile ammonium

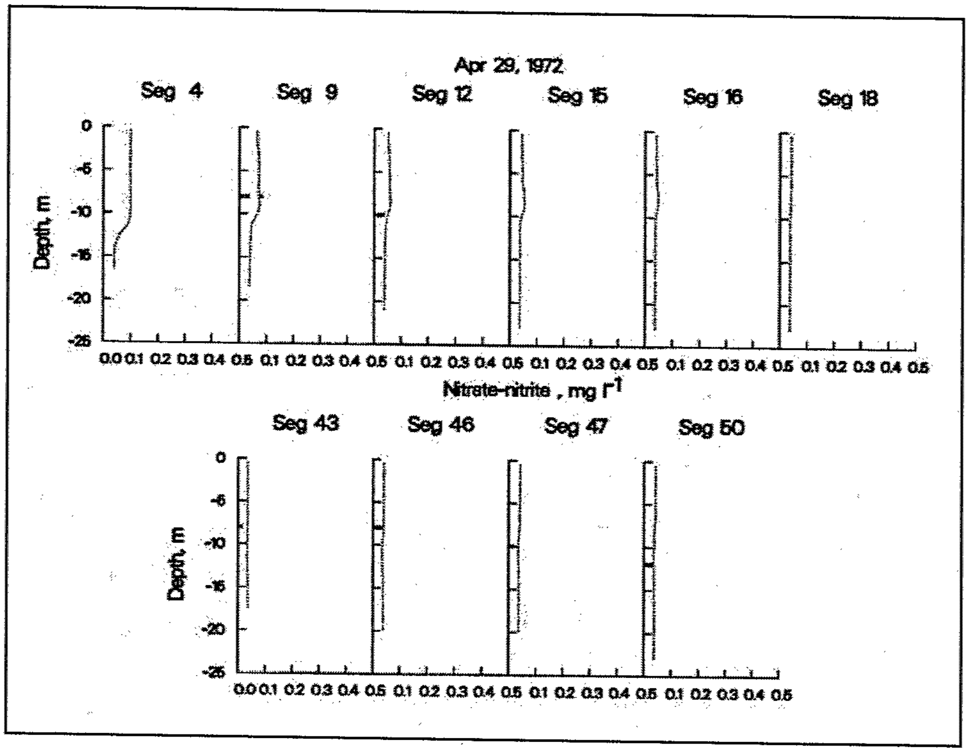

Figure 6-87. 1972 calibration profile nitrate-nitrite

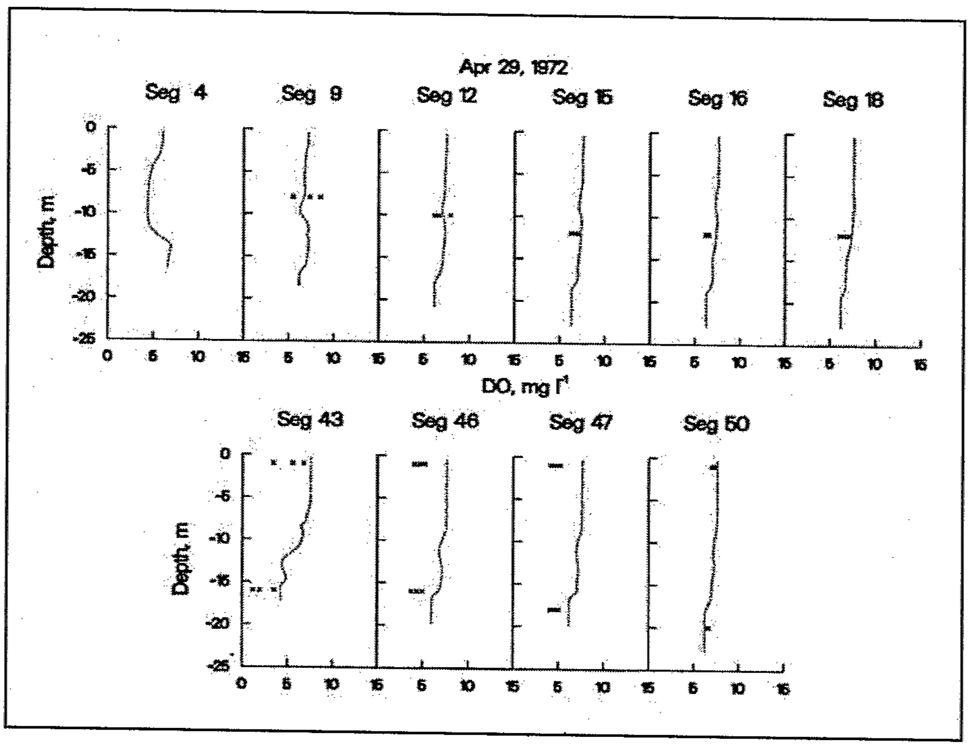

Figure 6-88. 1972 calibration profile dissolved oxygen

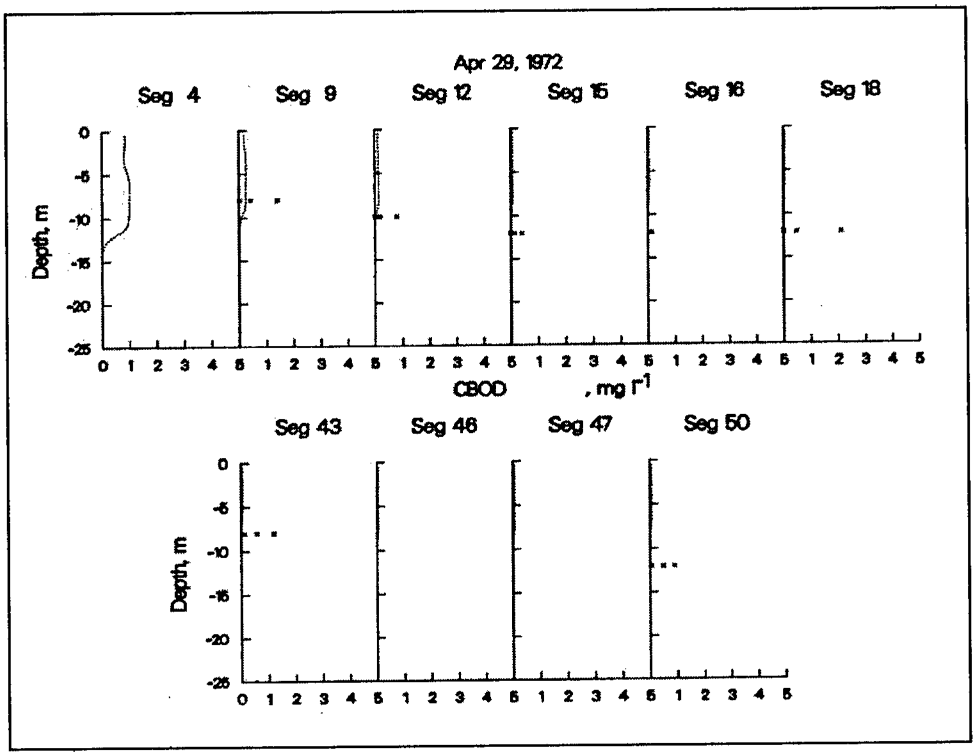

Figure 6-89. 1972 calibration profile CBOD

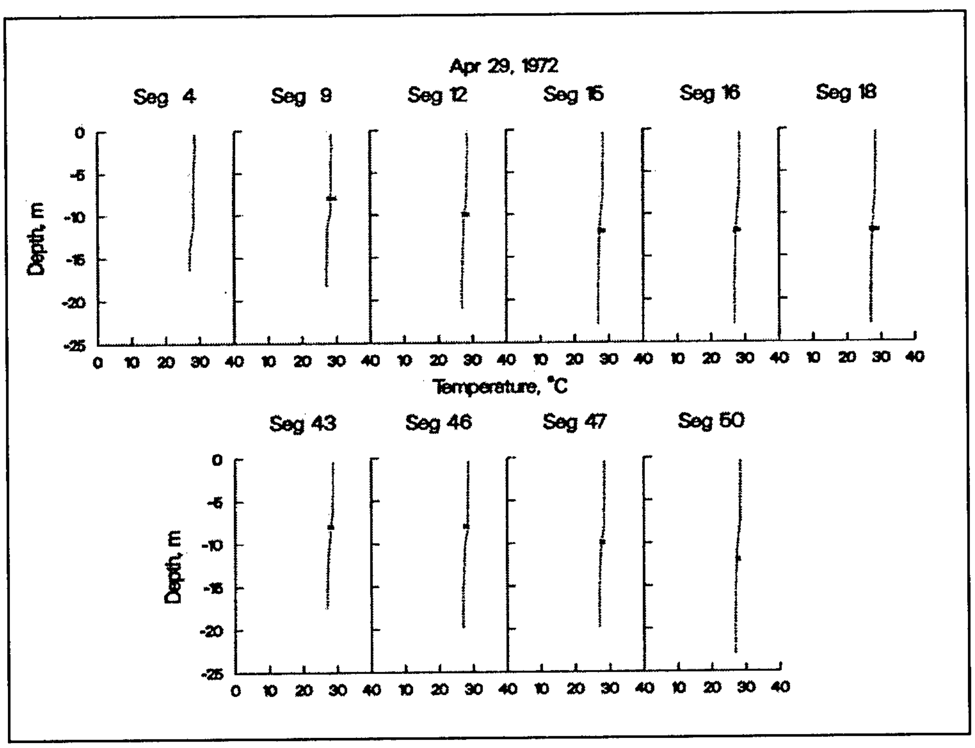

Figure 6-90. 1972 calibration profile temperature

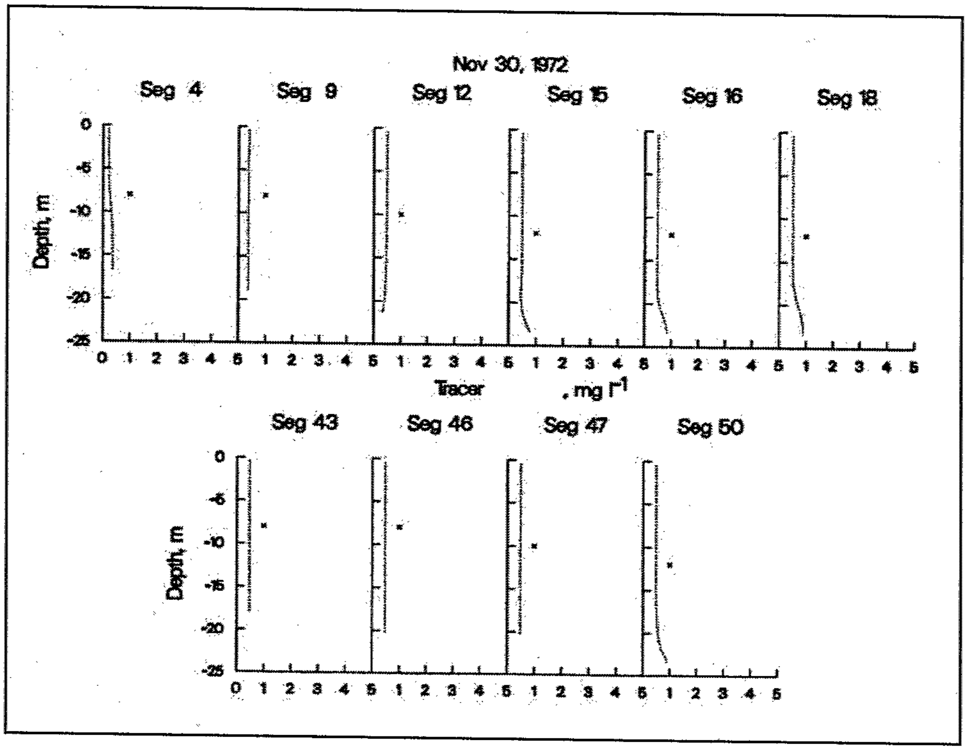

Figure 6-91. 1972 calibration profile tracer

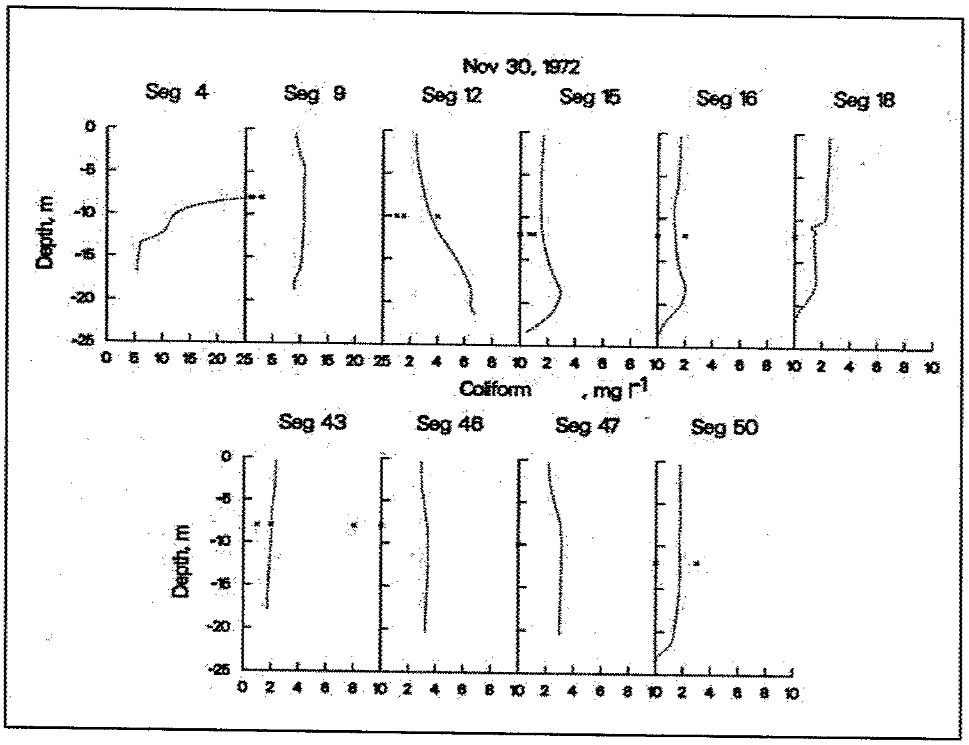

Figure 6-92. 1972 calibration profile coliform

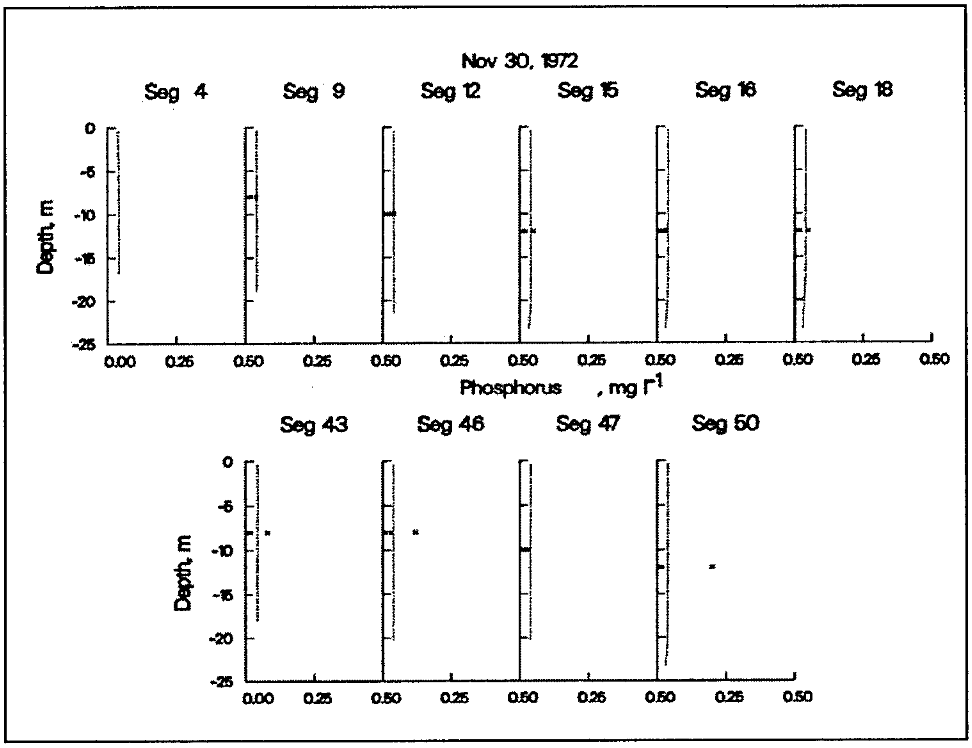

Figure 6-93. 1972 calibration profile phosphorus

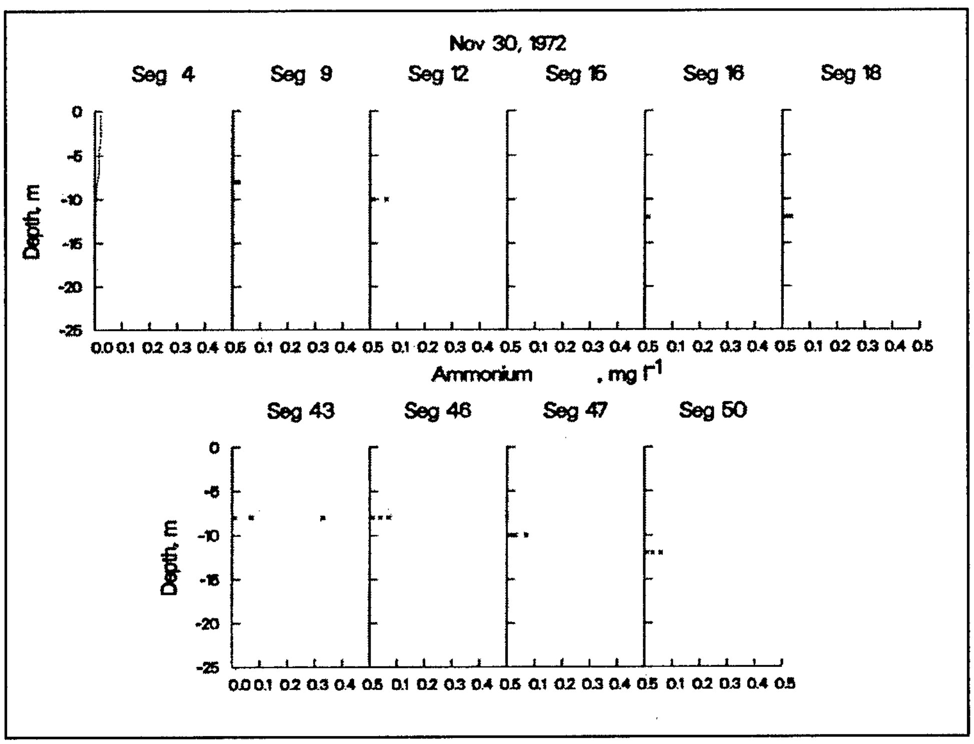

Figure 6-94. 1972 calibration profile ammonium

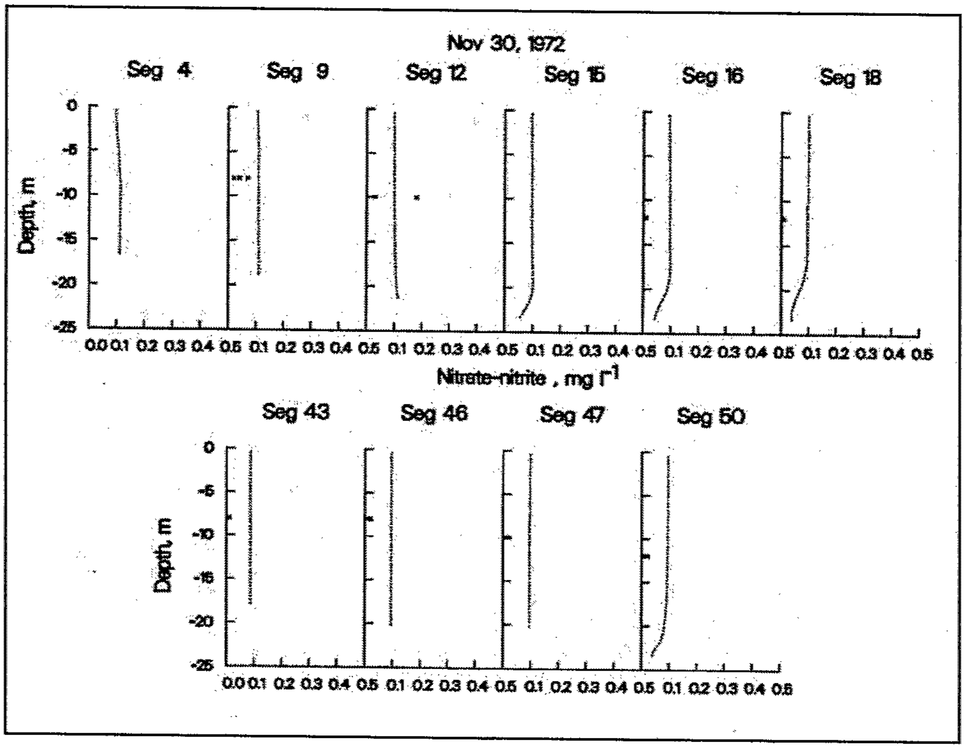

Figure 6-95. 1972 calibration profile nitrate-nitrite

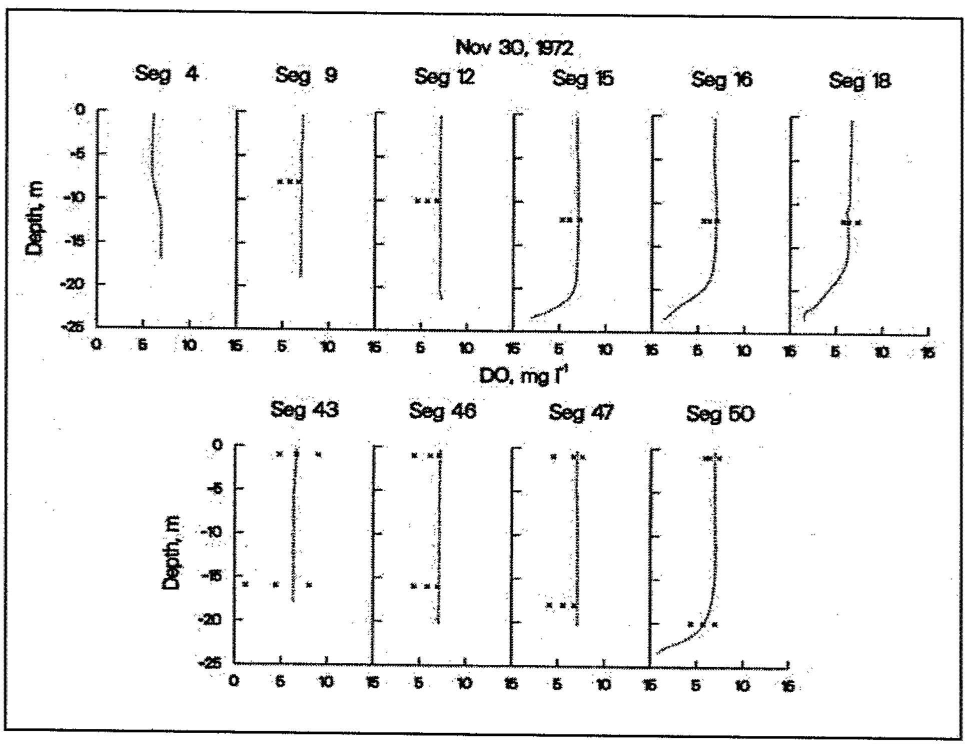

Figure 6-96. 1972 calibration profile dissolved oxygen

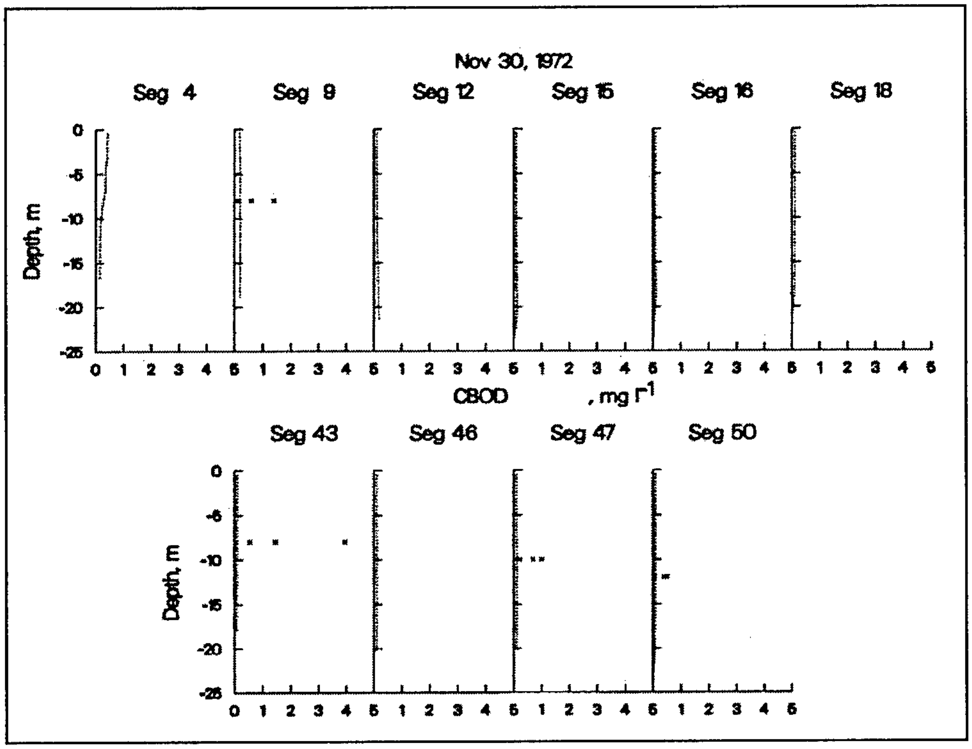

Figure 6-97. 1972 calibration profile CBOD

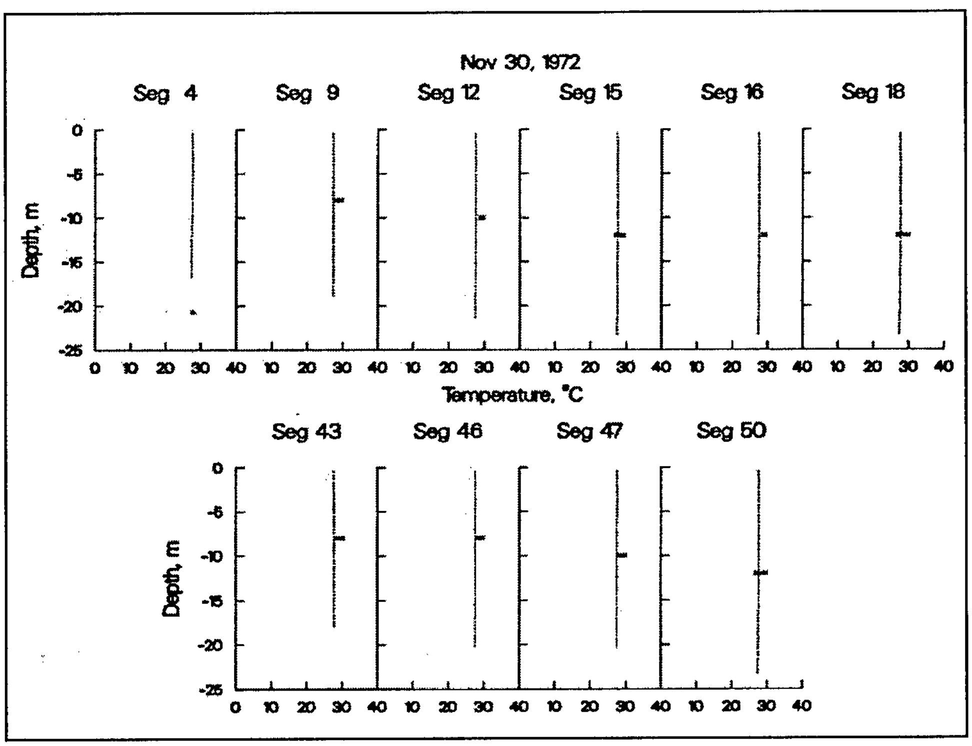

Figure 6-98. 1972 calibration profile temperature

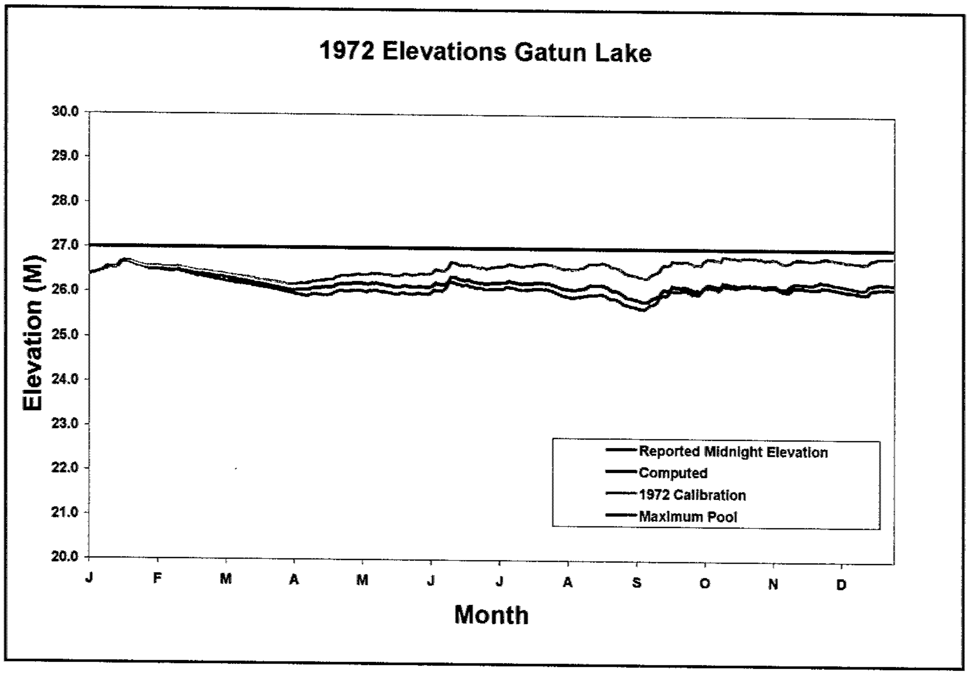

Figure 6-99. Recorded, computed, and 1972 calibration year water surface elevations

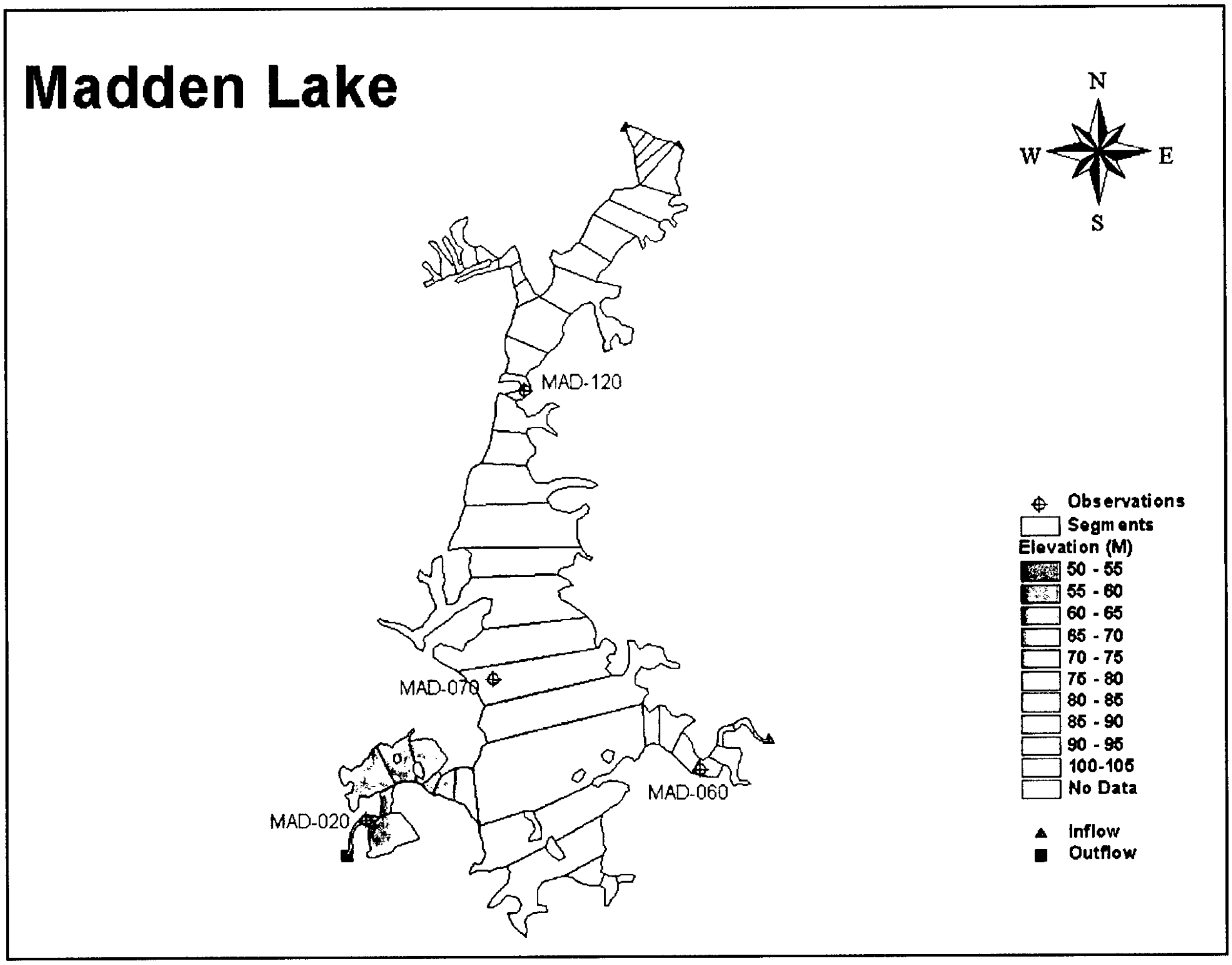

Figure 6-100. Madden lake schematic

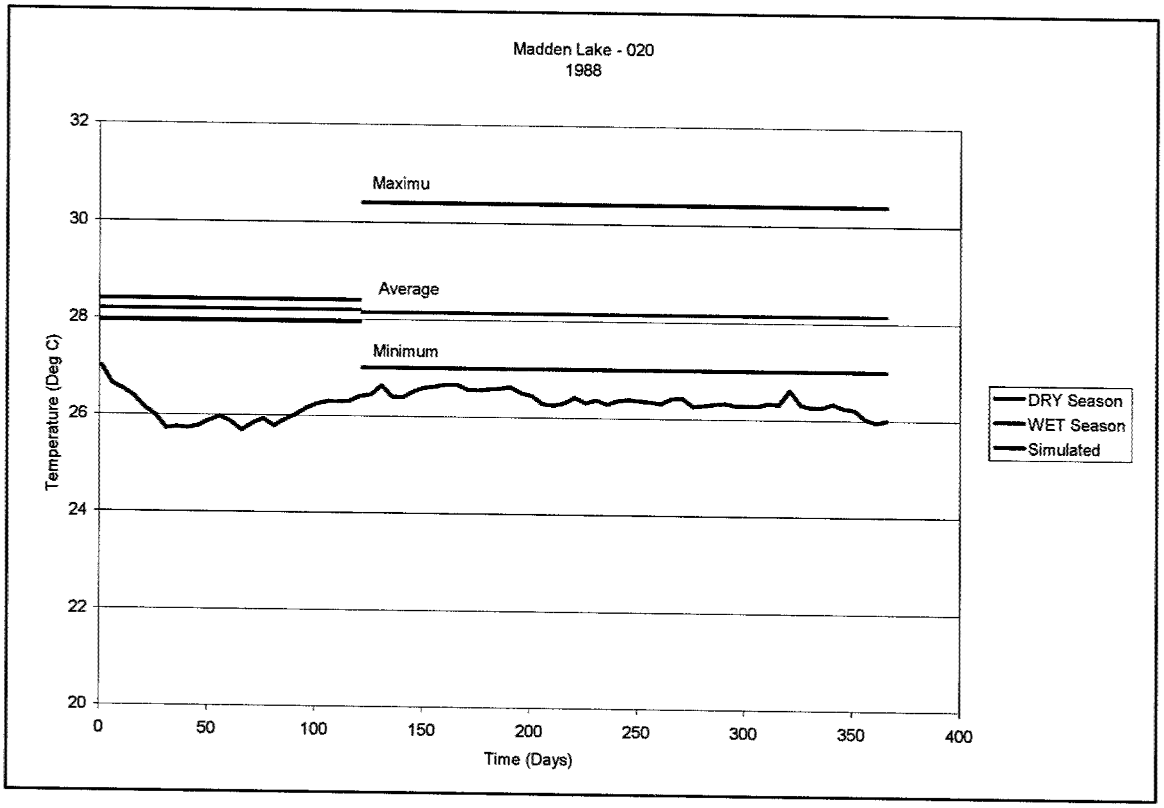

Figure 6-101. Mad-020 temperature (deg C)

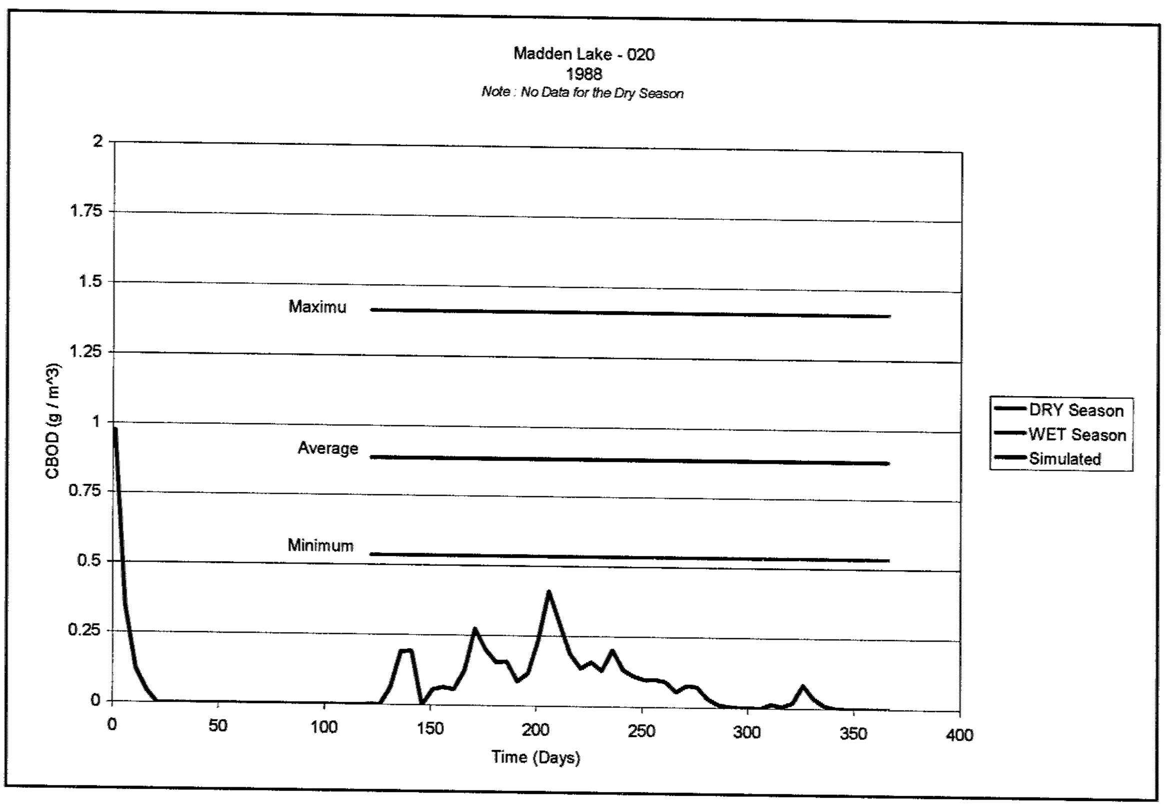

Figure 6-102. Mad-020 CBOD (g/m^3)

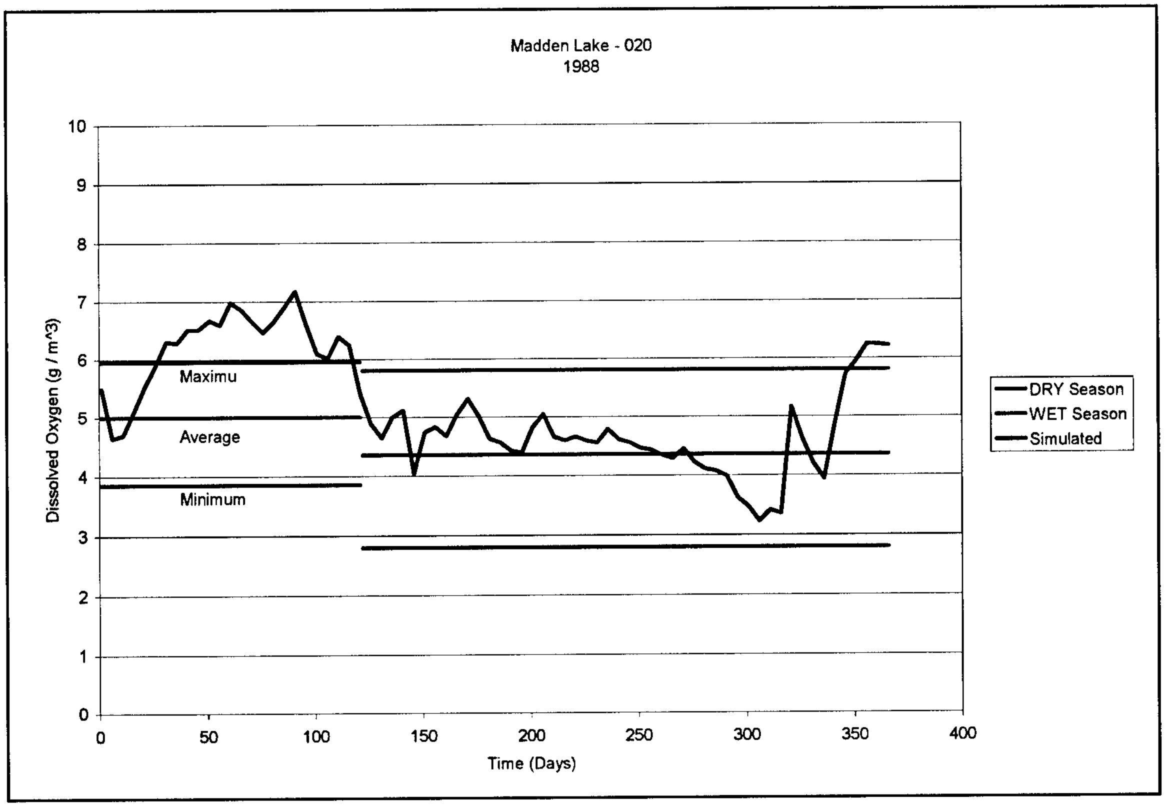

Figure 6-103. Mad-020 dissolved oxygen (g/m^3)

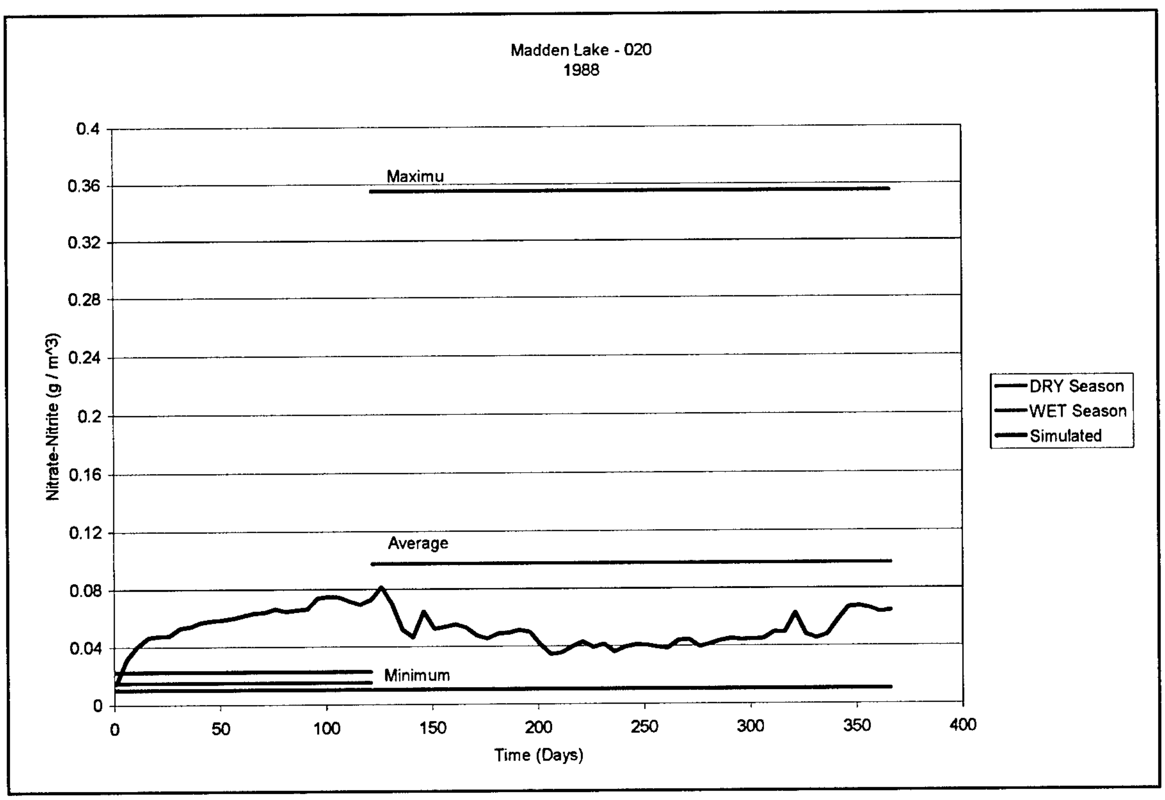

Figure 6-104. Ad-020 nitrate-nitrite (g/m^3)

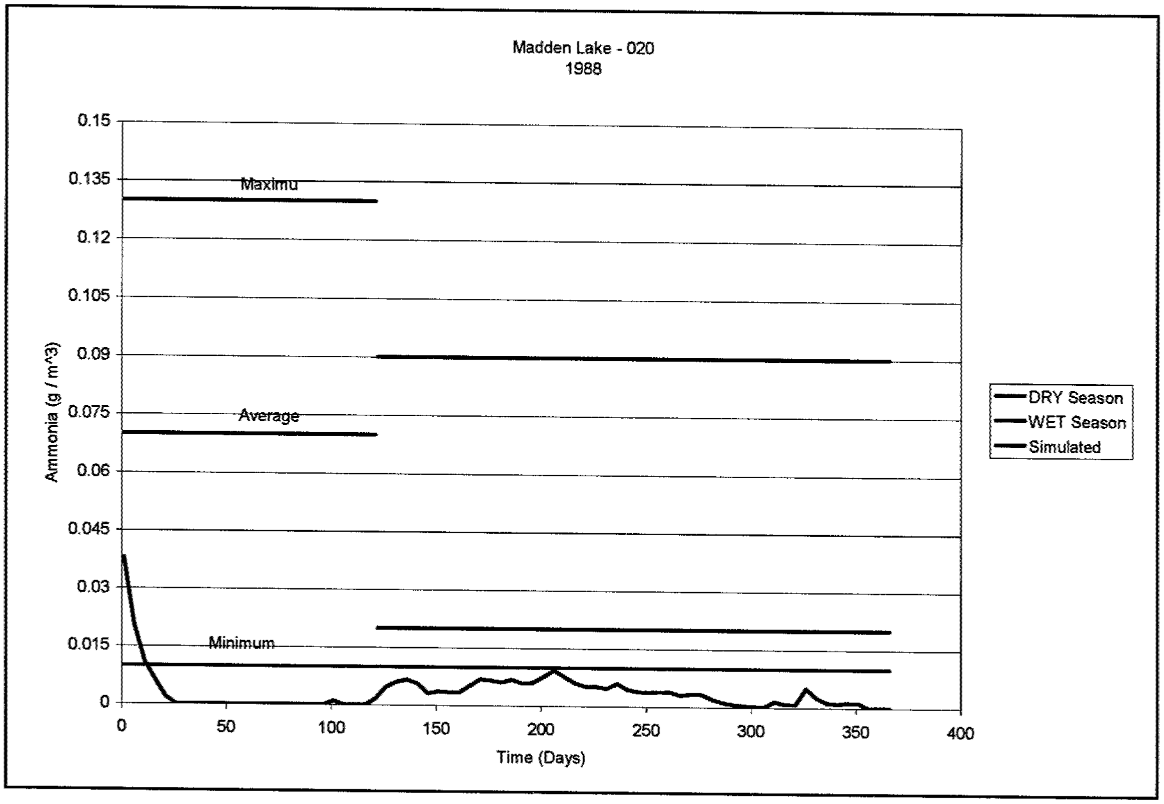

Figure 6-105. Mad-020 ammonia (g/m^3)

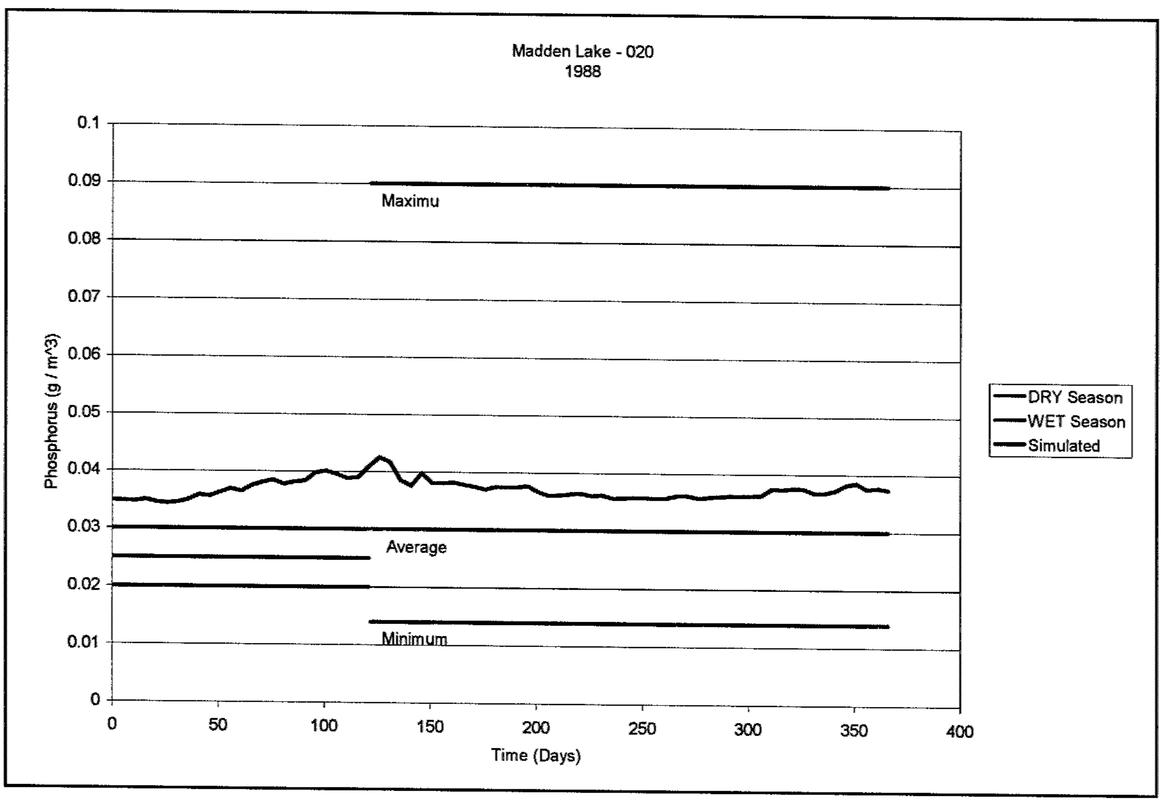

Figure 6-106. Mad-020 phosphorus (g/m^3)

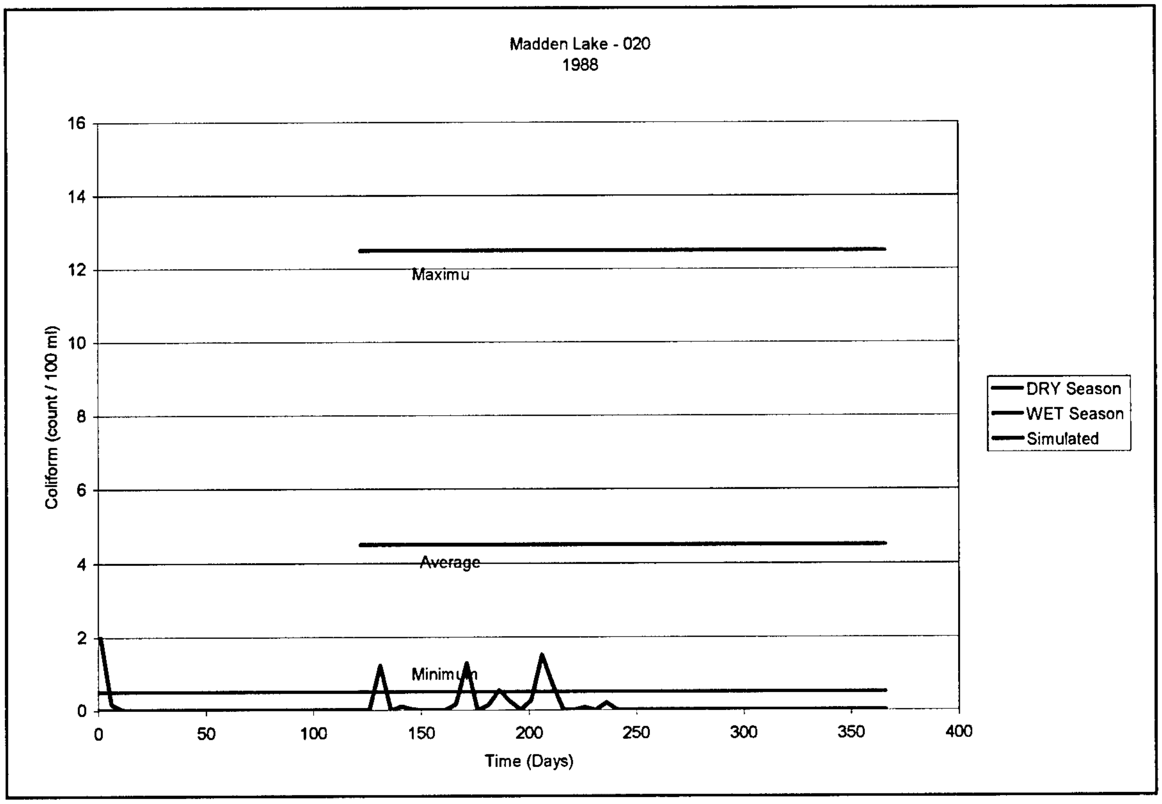

Figure 6-107. Mad-020 coliform (count / 100 ml)

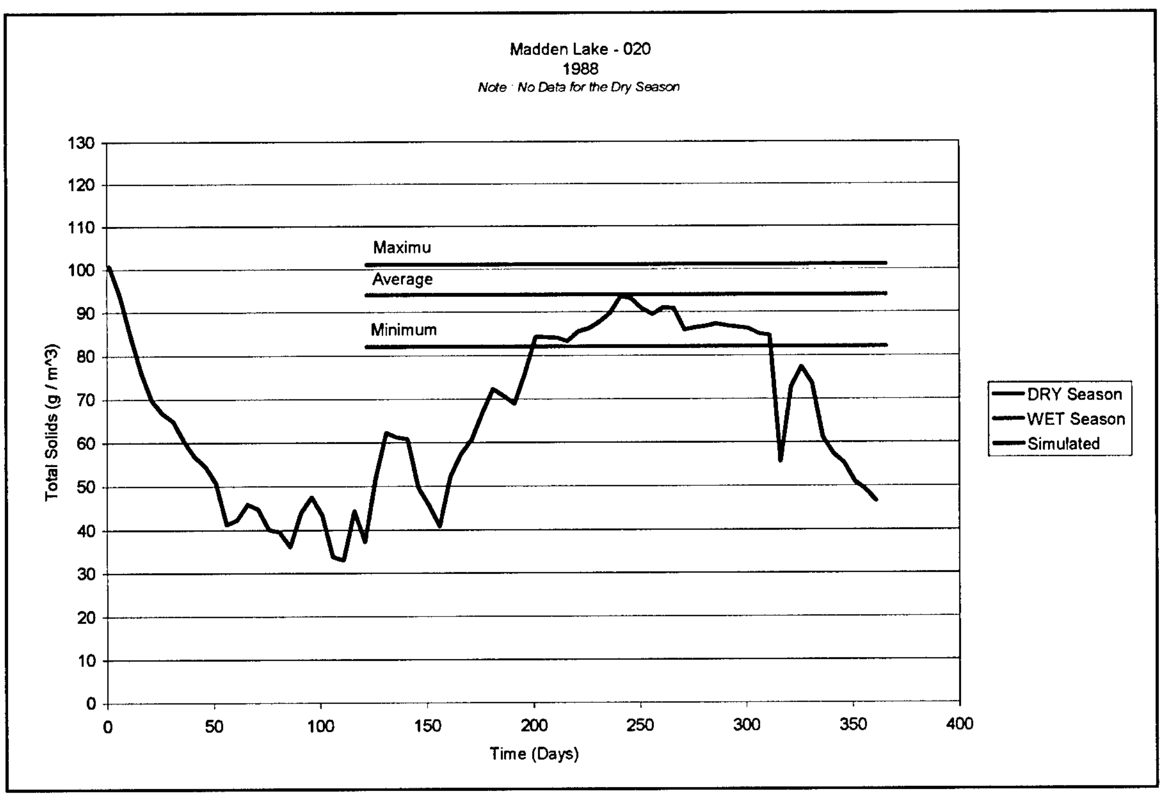

Figure 6-108. Mad-020 total solids (g/m^3)

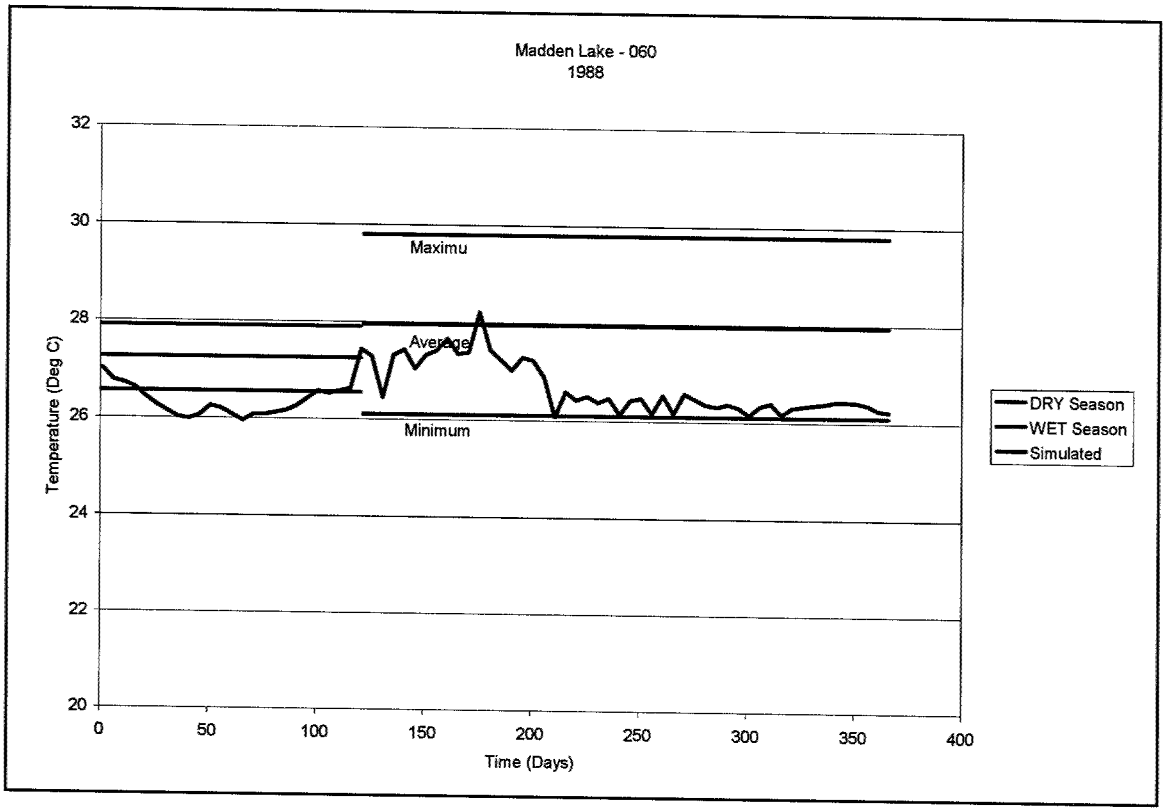

Figure 6-109. Mad-060 temperature (deg C)

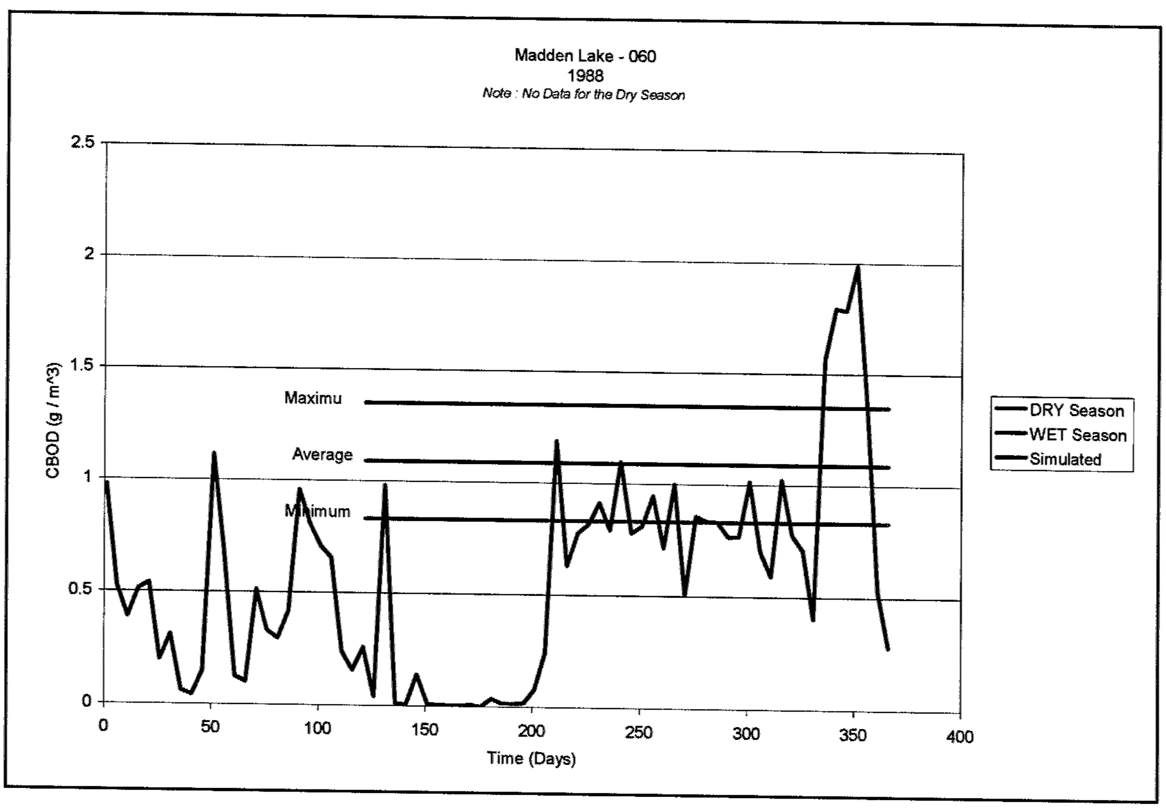

Figure 6-110. Mad-060 CBOD (g/m^3)

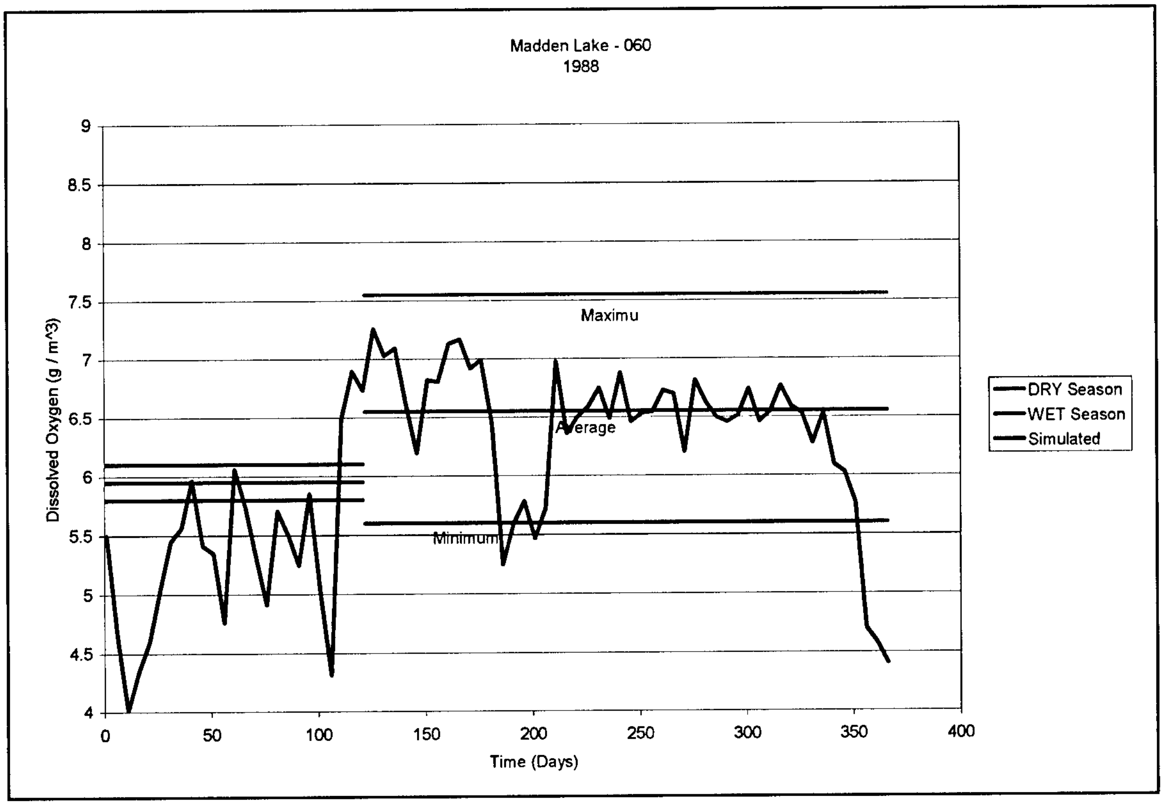

Figure 6-111. Mad-060 dissolved oxygen (g/m^3)

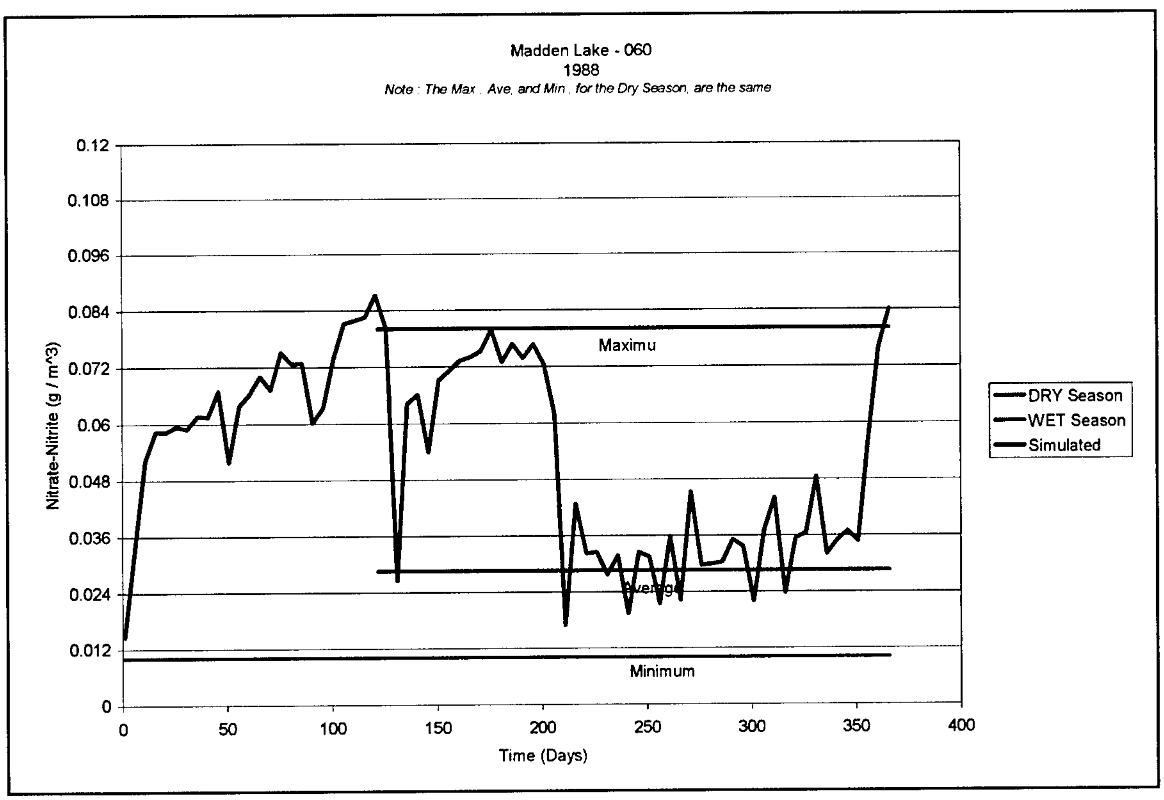

Figure 6-112. Mad-060 nitrate-nitrite (g/m^3)

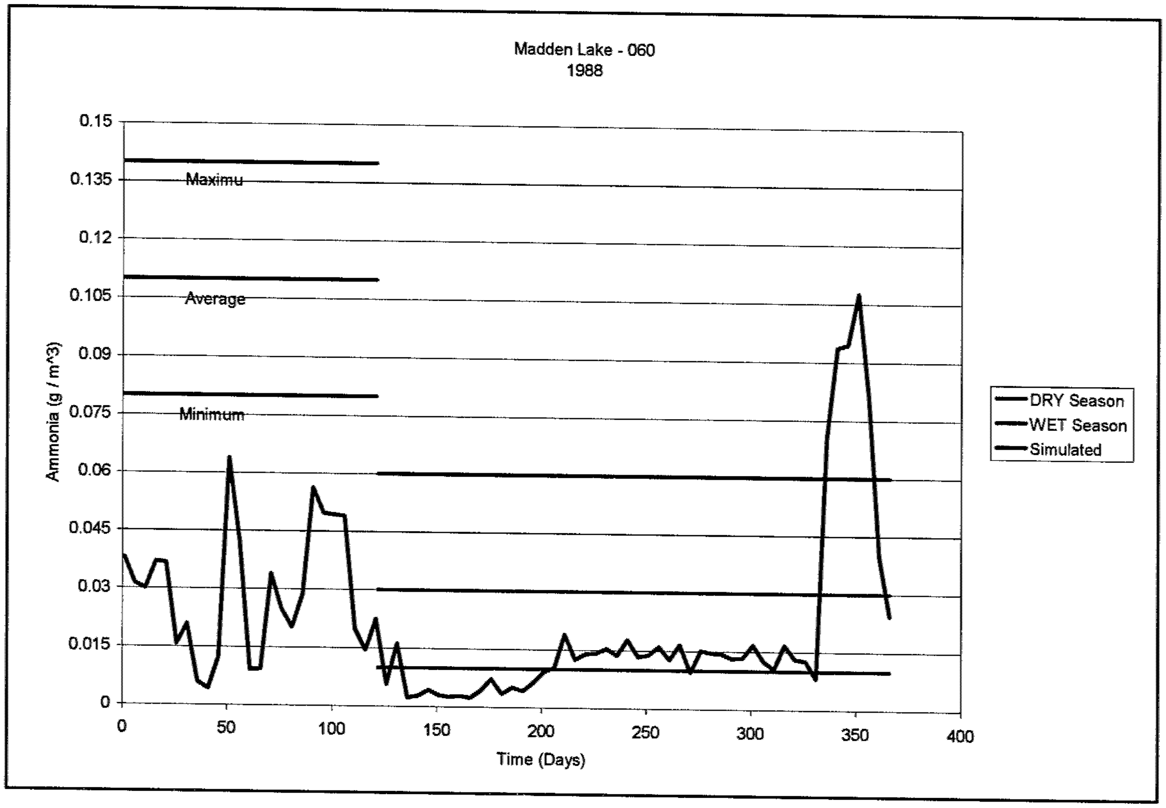

Figure 6-113. Mad-060 ammonia (g/m^3)

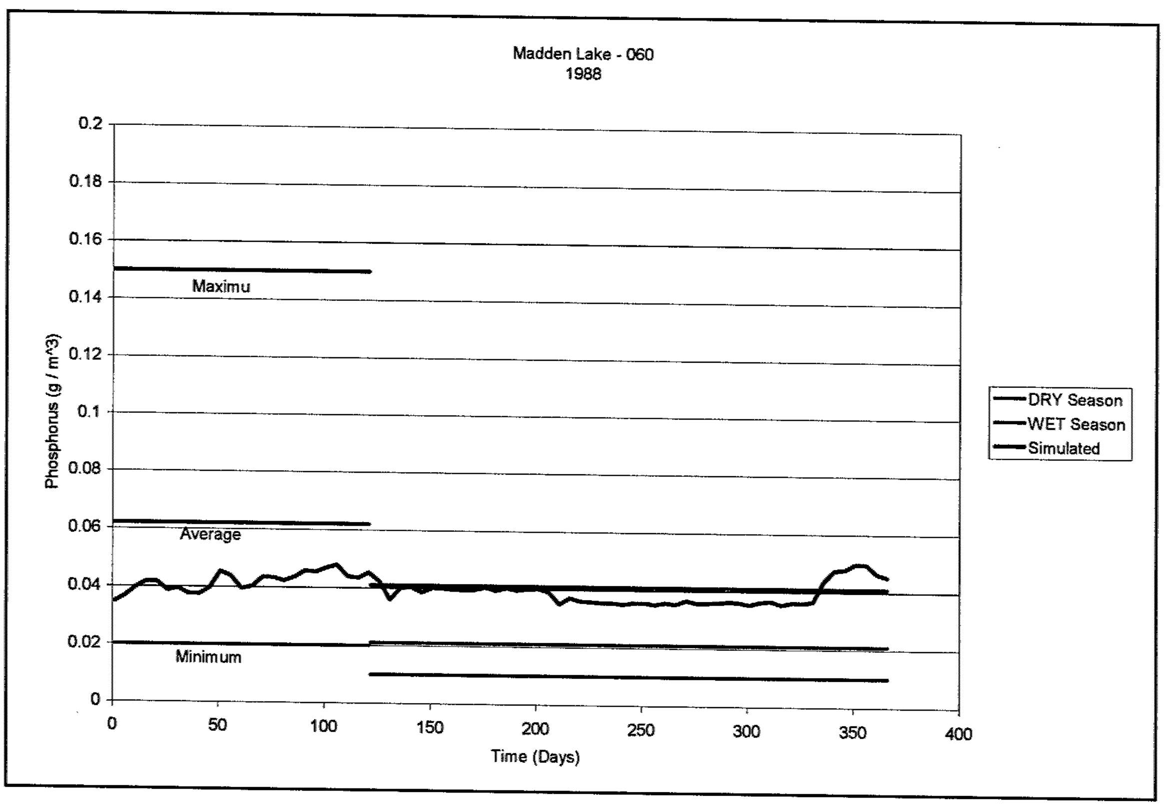

Figure 6-114. Mad-060 phosphorus (g/m^3)

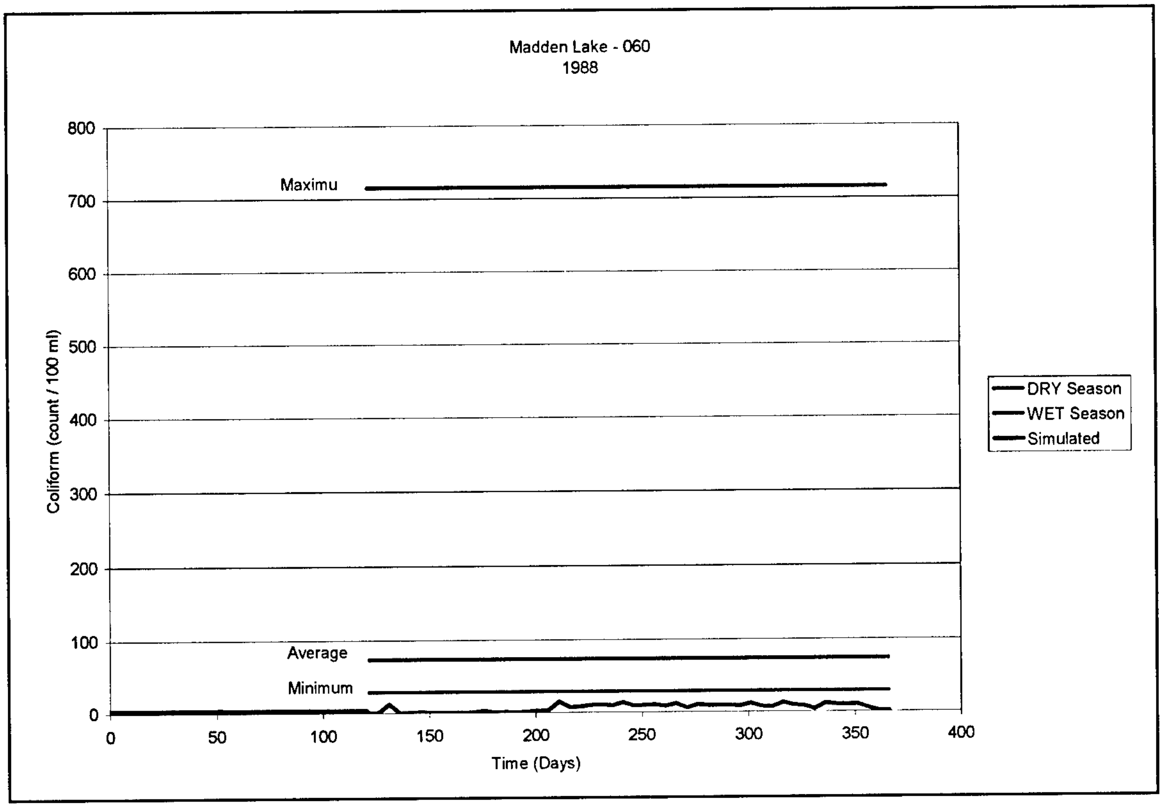

Figure 6-115. Mad-060 coliform (count / 100 ml)

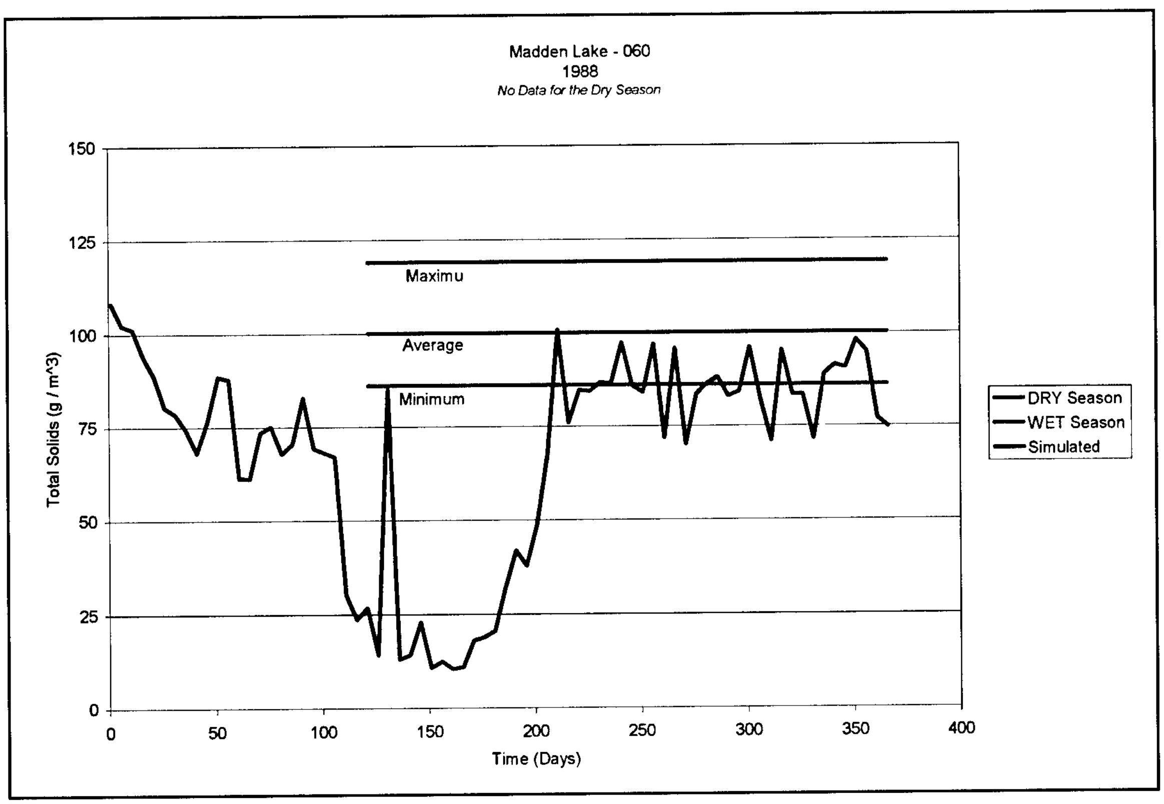

Figure 6-116. Mad-060 total solids (g/m^3)

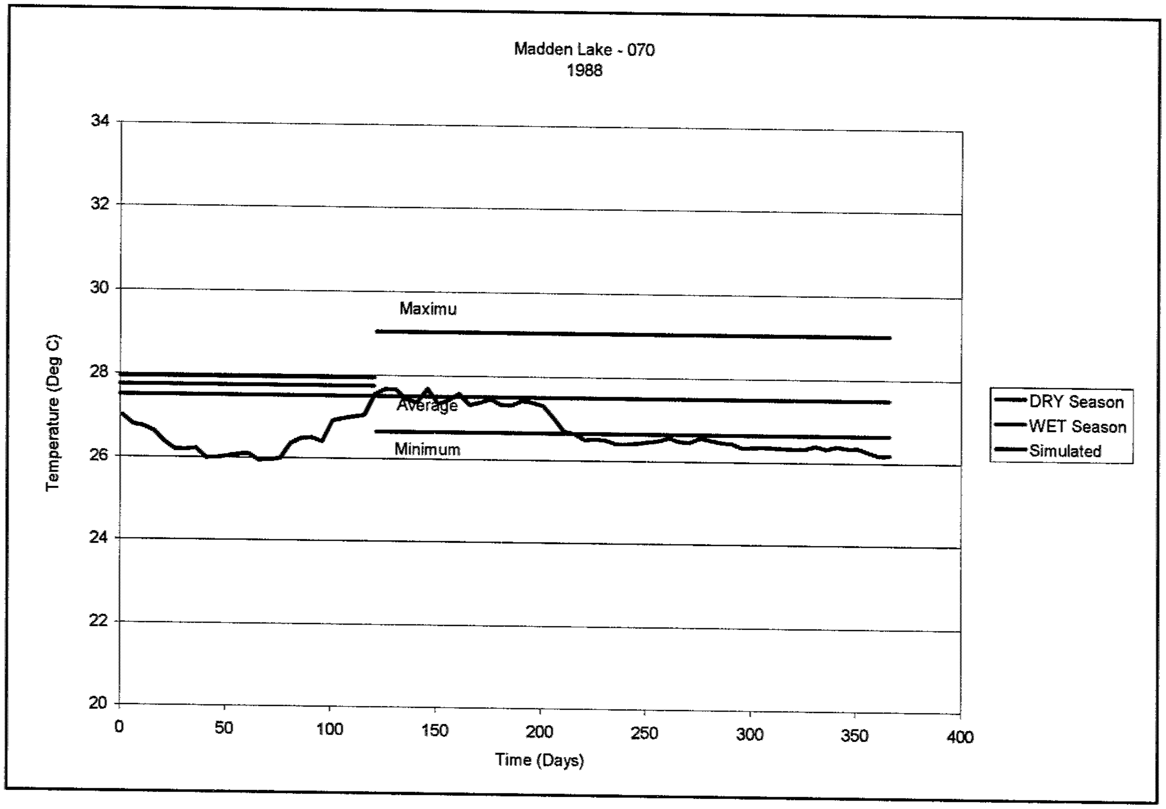

Figure 6-117. Mad-070 temperature (deg C)

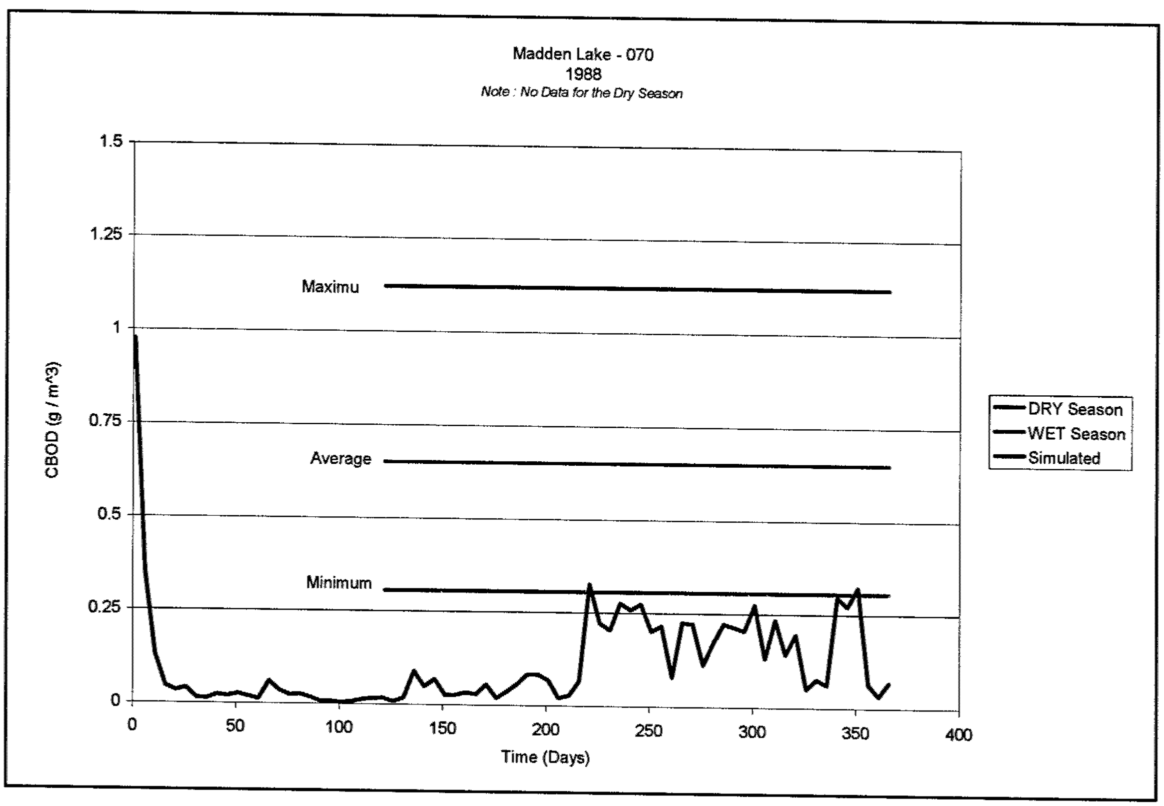

Figure 6-118. Mad-070 CBOD (g/m^3)

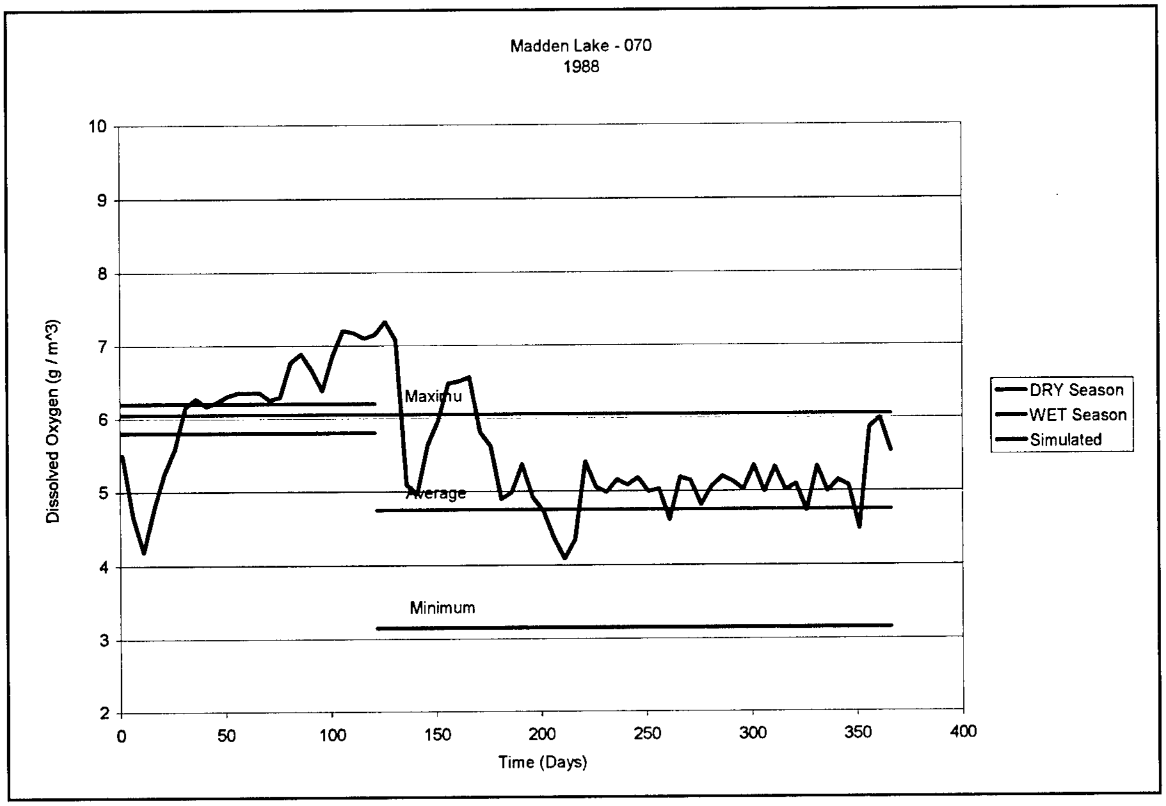

Figure 6-119. Mad-070 dissolved oxygen (g/m^3)

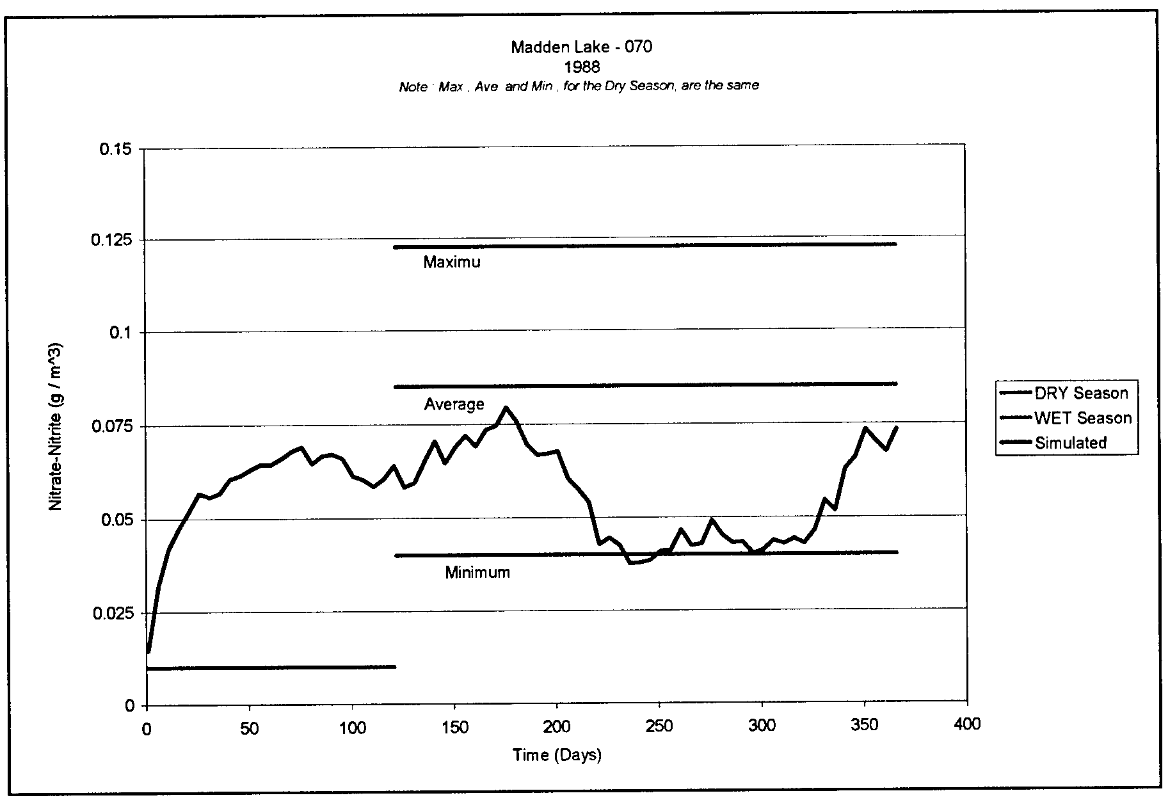

Figure 6-120. Mad-070 nitrate-nitrite (g/m^3)

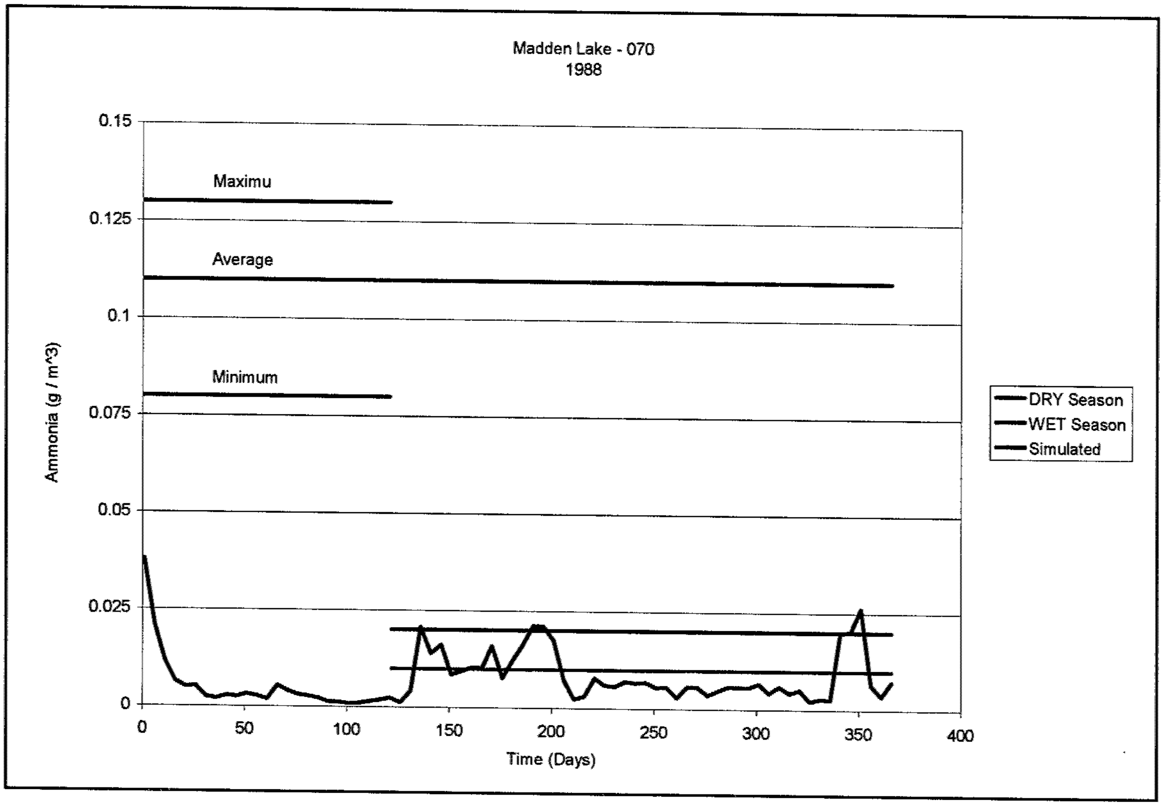

Figure 6-121. Mad-070 ammonia (g/m^3)

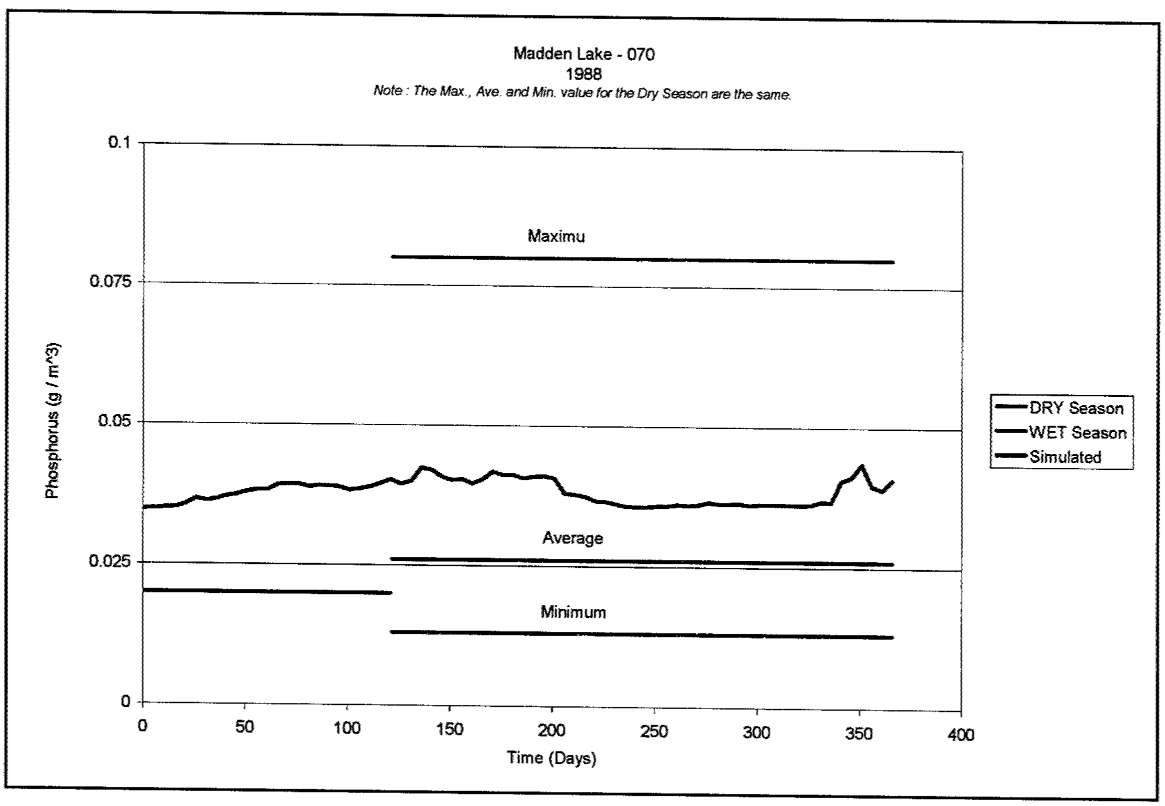

Figure 6-122. Mad-070 phosphorus (g/m^3)

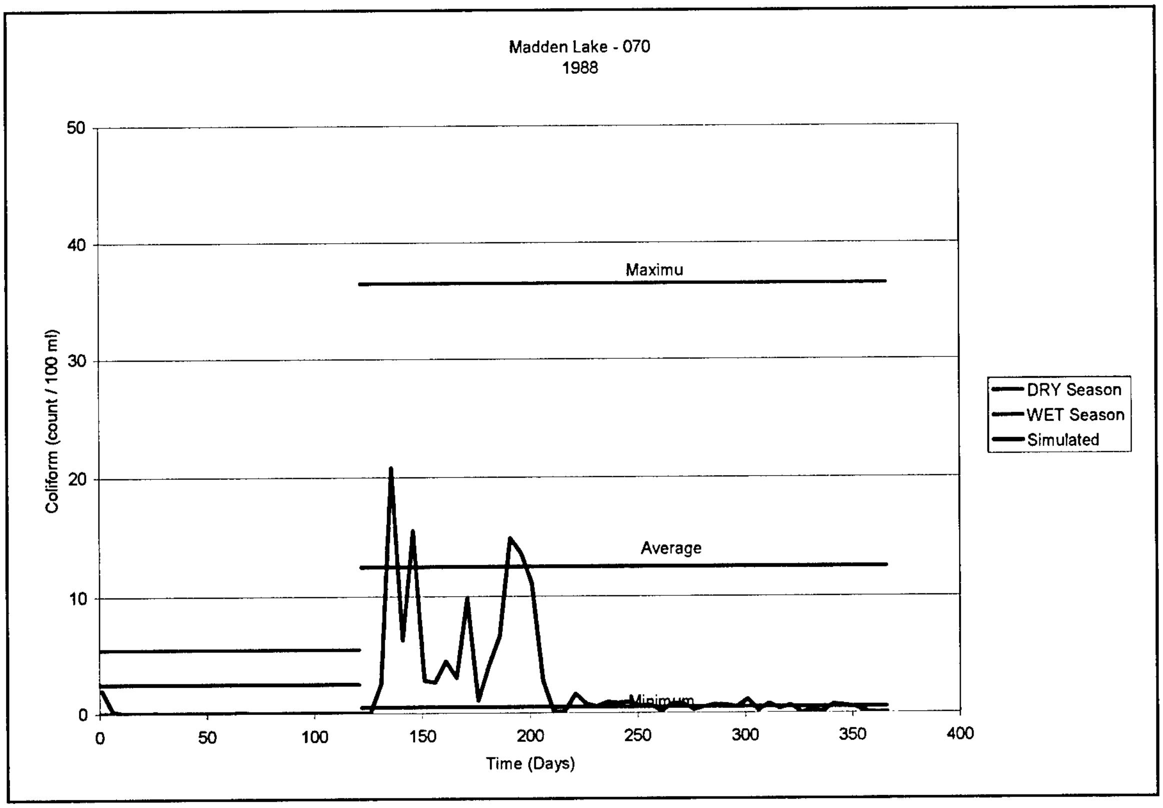

Figure 6-123. Mad-070 coliform (count / 100 ml)

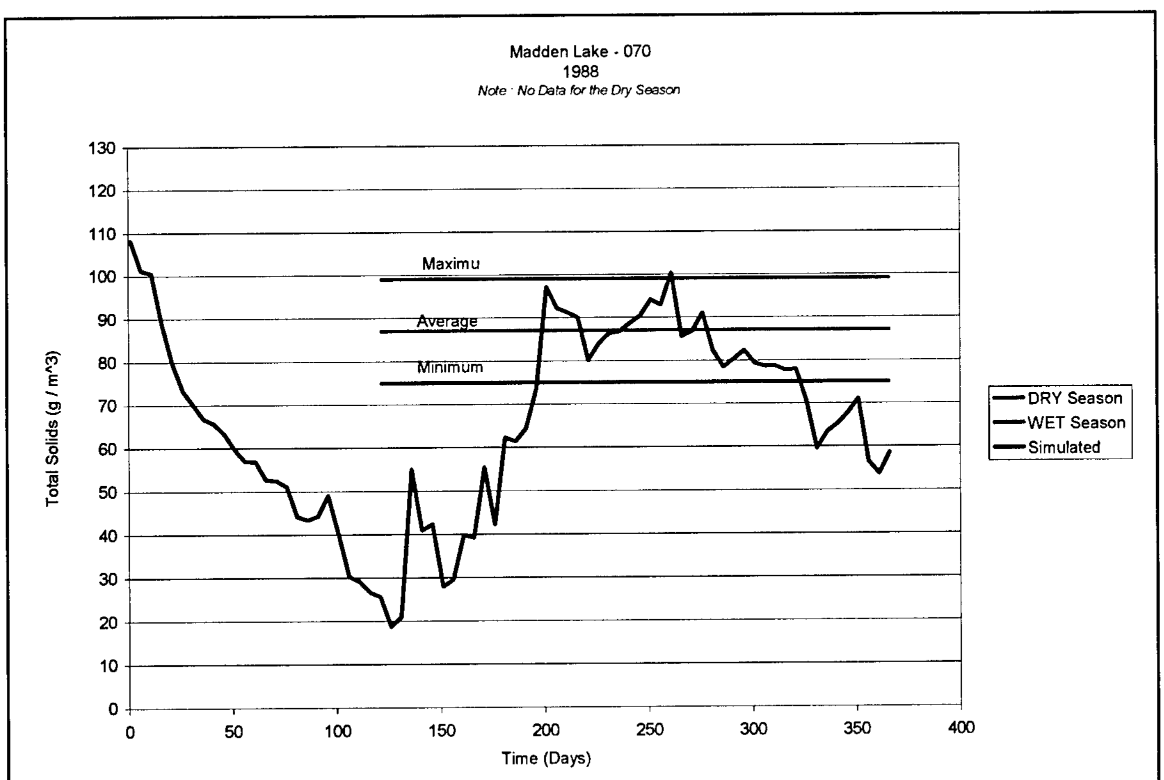

Figure 6-124. Mad-070 total solids (g/m^3)

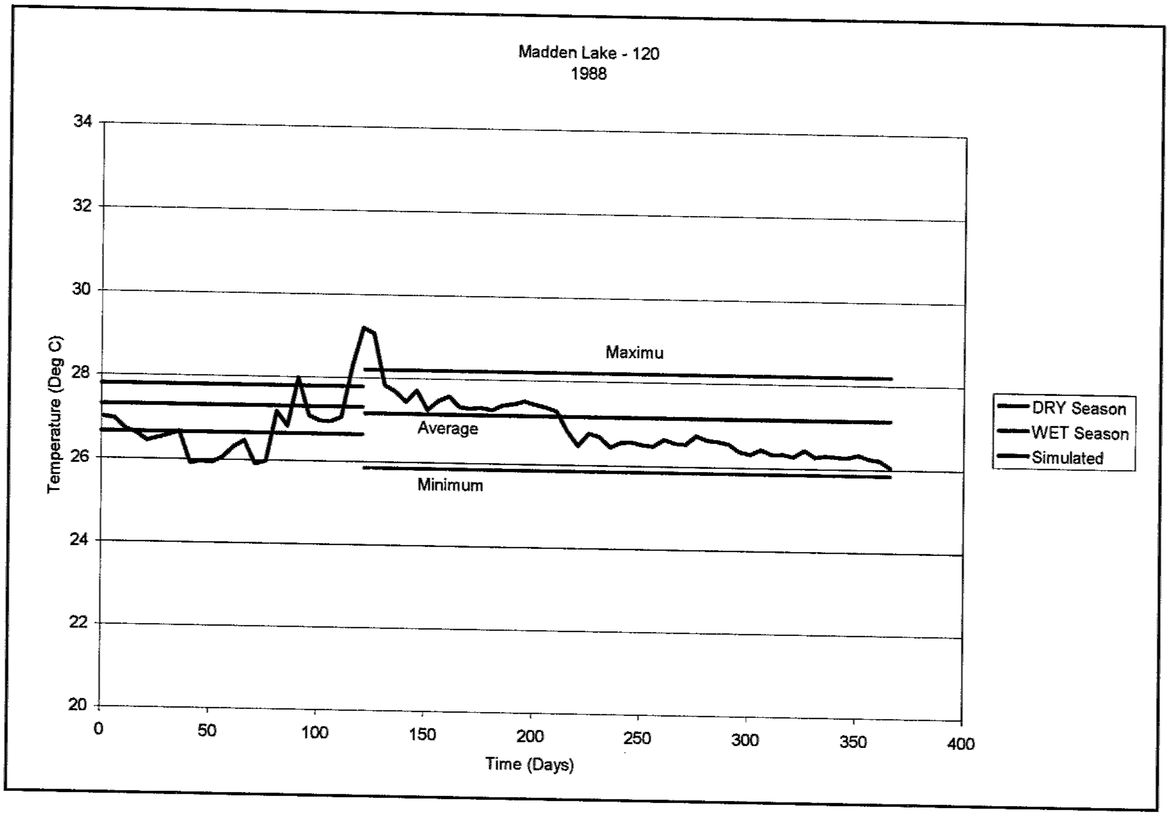

Figure 6-125. Mad-120 temperature (deg C)

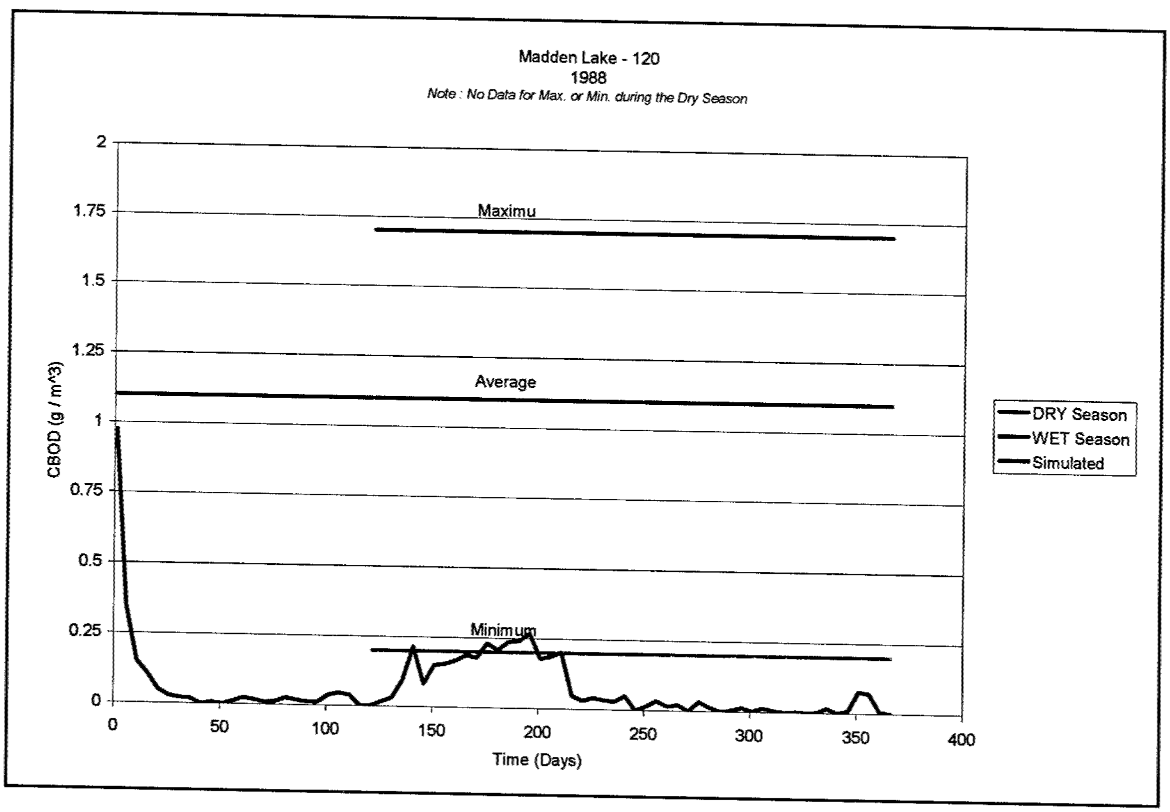

Figure 6-126. Mad-120 CBOD (g/m^3)

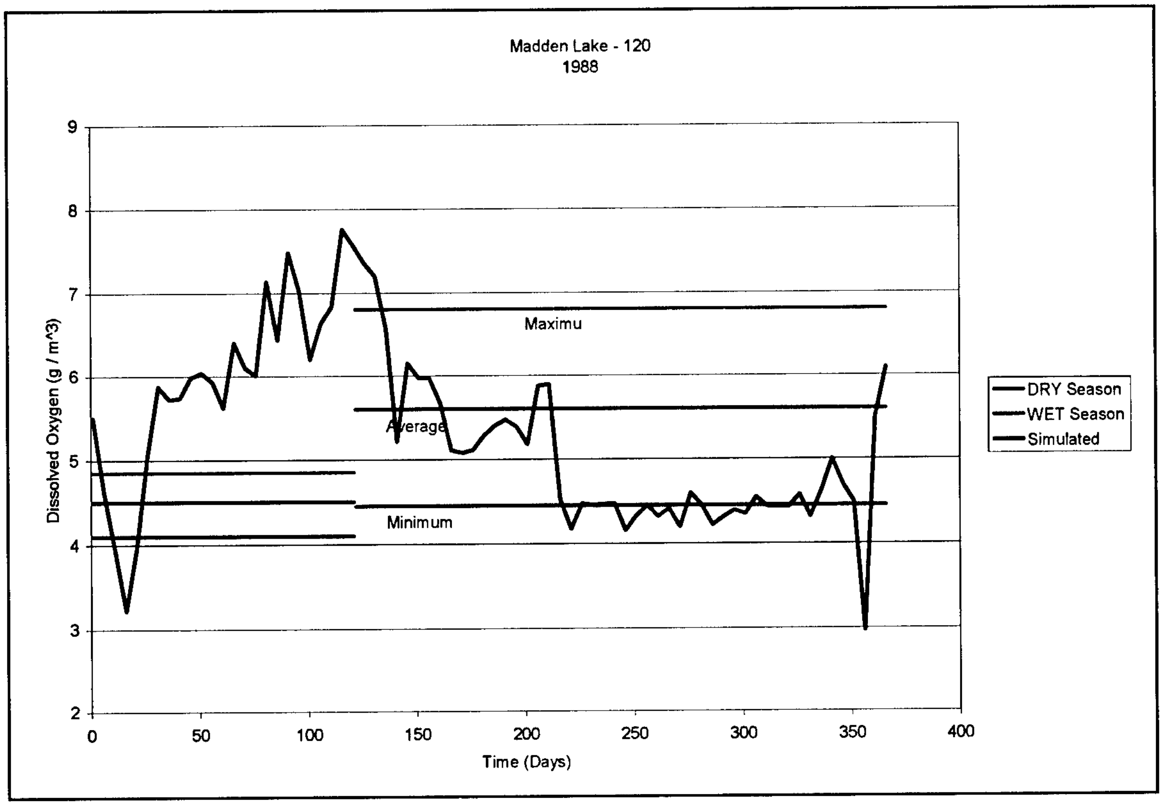

Figure 6-127. Mad-120 dissolved oxygen (g/m^3)

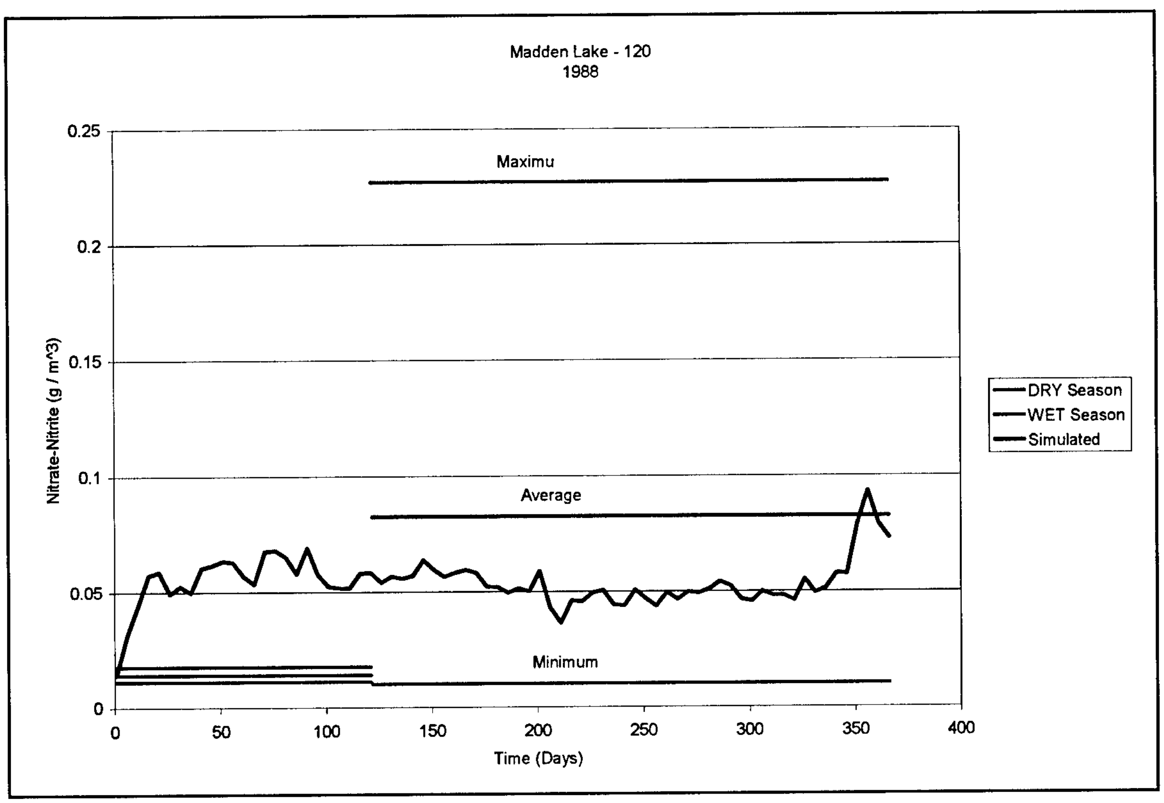

Figure 6-128. Mad-120 nitrate-nitrite (g/m^3)

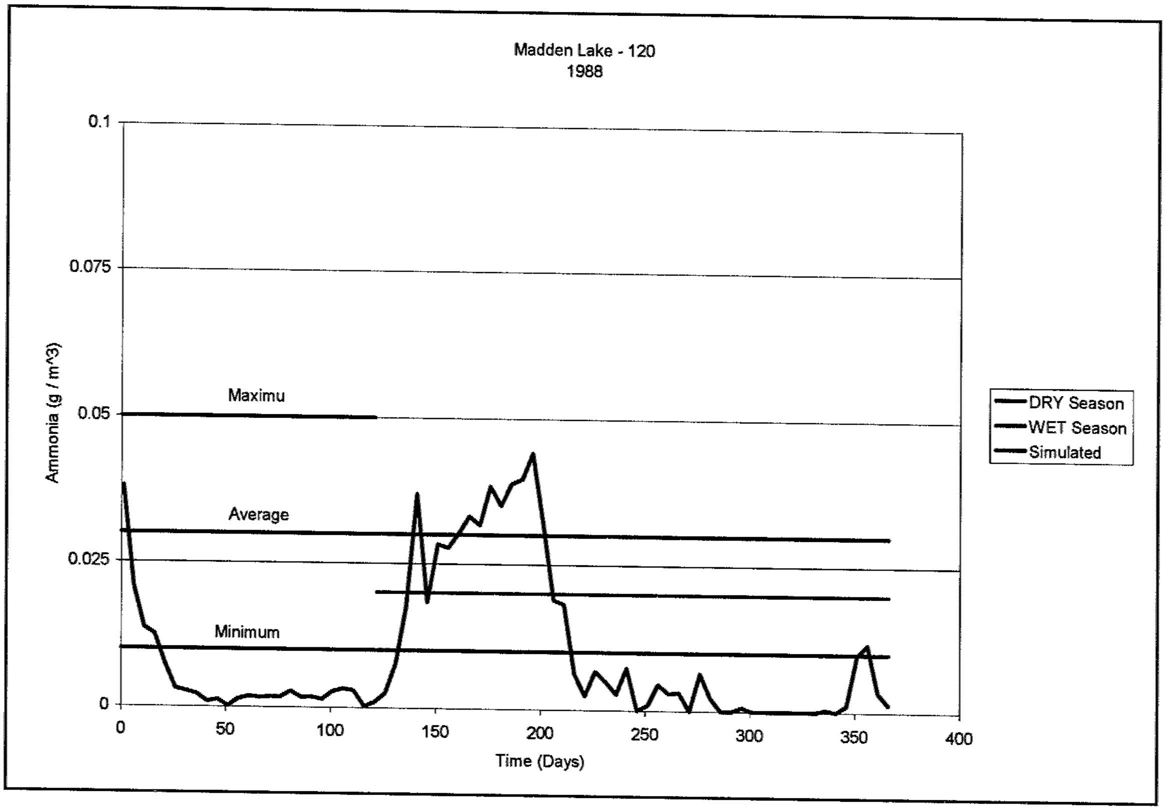

Figure 6-129. Mad-120 ammonia (g/m^3)

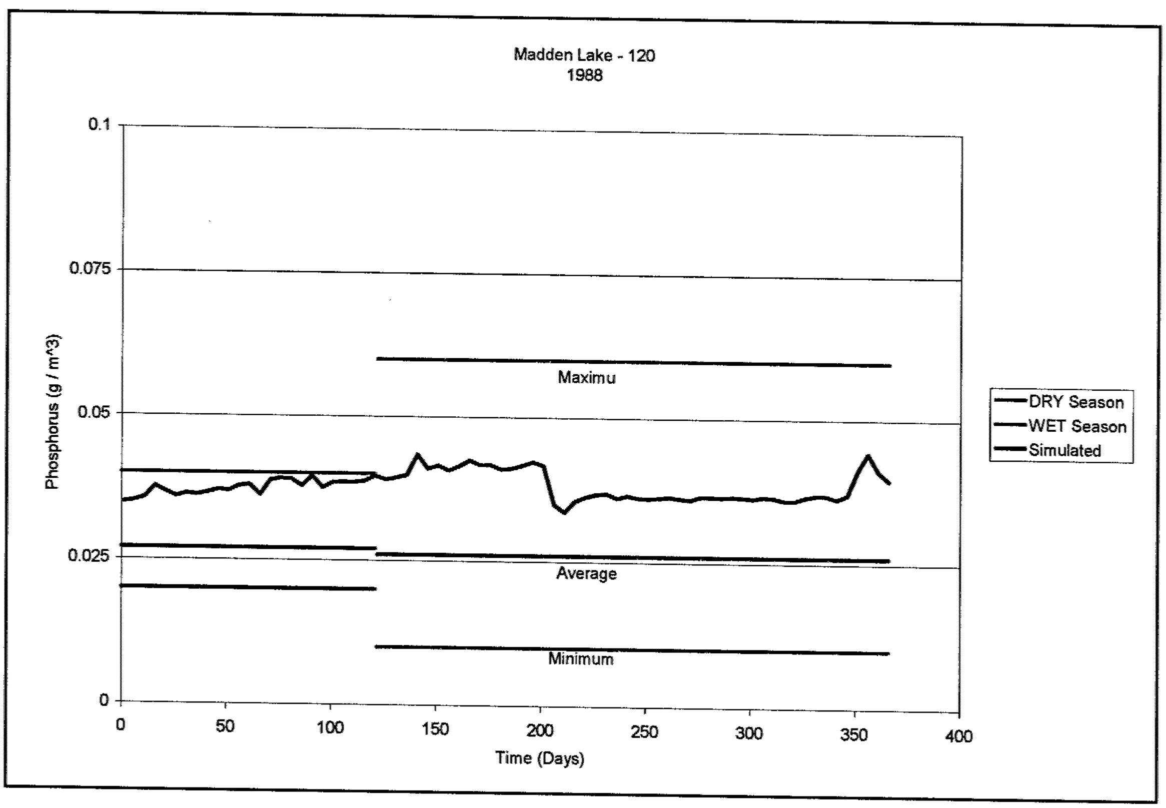

Figure 6-130. Mad-120 phosphorus (g/m^3)

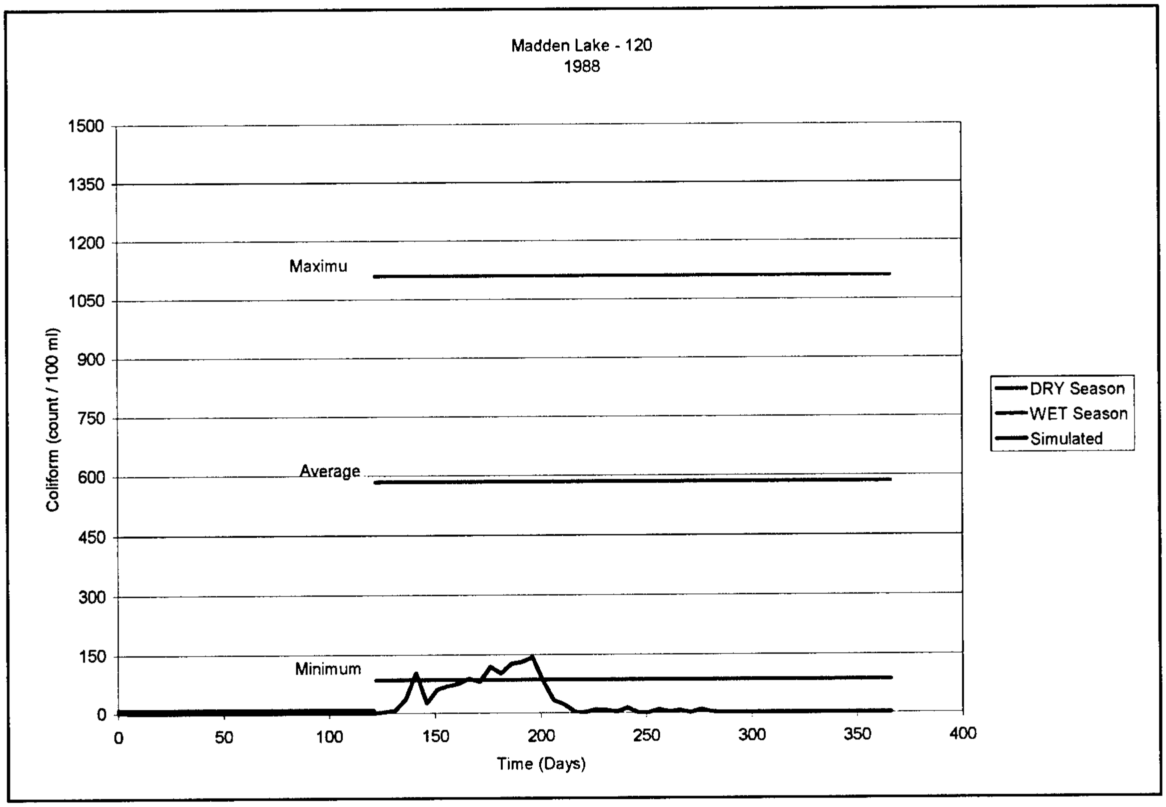

Figure 6-131. Mad-120 coliform (count / 100 ml)

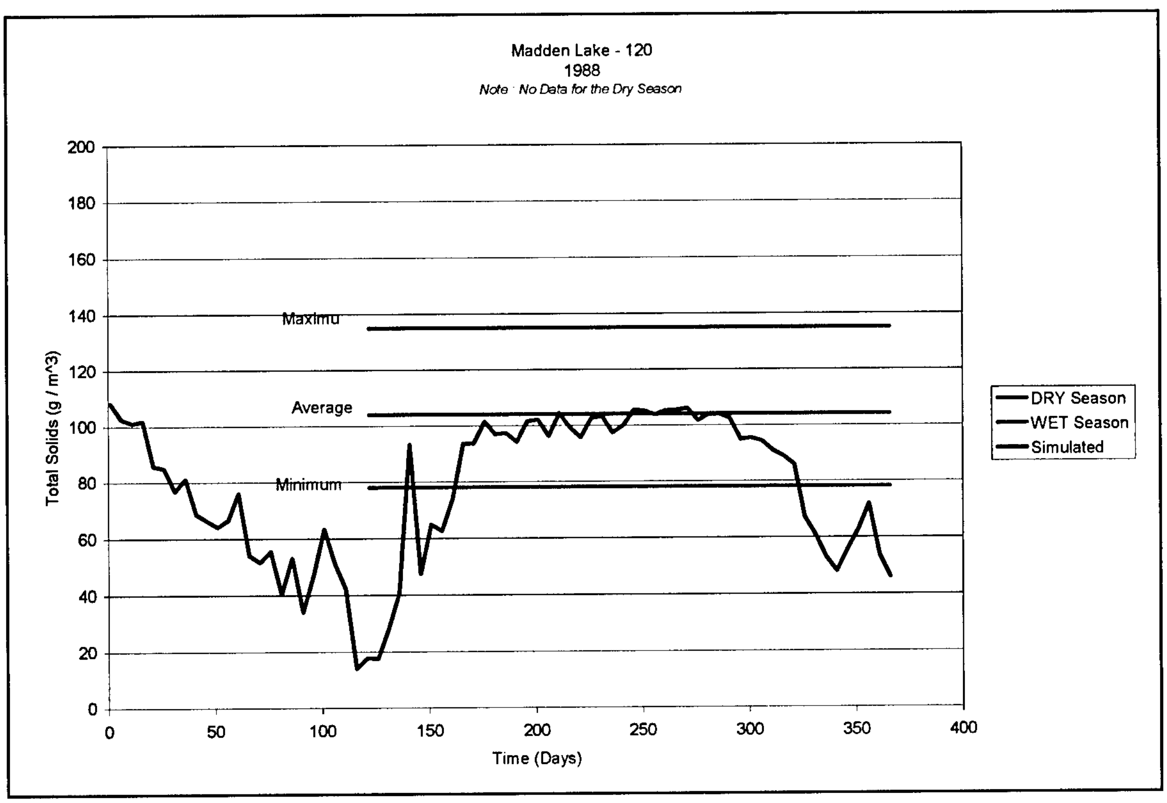

Figure 6-132. Mad-120 total solids (g/m^3)

7 Western Watershed Proposed Reservoirs

Three proposed reservoirs constitute the western watershed: 1) Rio Indio; 2) Caño Sucio; and 3) Coclé del Norte (Figure 7-1). CE-QUAL-W2 was set up for each of these reservoirs however water quality and inter-basin transfers were simulated for only Rio Indio. Initially it was proposed that water quality simulations would be performed for all three reservoirs. However, due to time constraints and the limited information available for Coclé del Norte and Caño Sucio, it was determined that the thrust of this study should be the water quality of the proposed reservoir on the Rio Indio and the impact that its waters would have on Gatun Lake including M&I water supply needs via inter-basin transfers. Consequently, no water quality results for the proposed Coclé del Norte and Caño Sucio reservoirs are presented.

Rio Indio

The Rio Indio Watershed is located adjacent to the western side of the Panama Canal watershed. The proposed Rio Indio project would contribute measurably to the hydrologic reliability of the Panama Canal to provide water for M&I needs and canal operation. The Rio Indio flows northward from the Continental Divide to the Atlantic Ocean. The headwaters of the watershed begin at elevation 1000 m MSL approximately 75 km inland and fall to mean sea level at it's mouth. The distribution of the average annual rainfall over the Rio Indio watershed varies from a high of 3500 mm in the middle watershed to a low of 2500 mm at the eastern limits of the watershed.

Inter-basin transfer from Rio Indio Reservoir to Gatun Lake would be accomplished via tunnel. At the upper end of the tunnel there are questions regarding the need for a mulit-level intake which would facilitate selective withdrawal operations. Selective withdrawal enables waters to be withdrawn from various layers and blended to generate water of a desired quality.

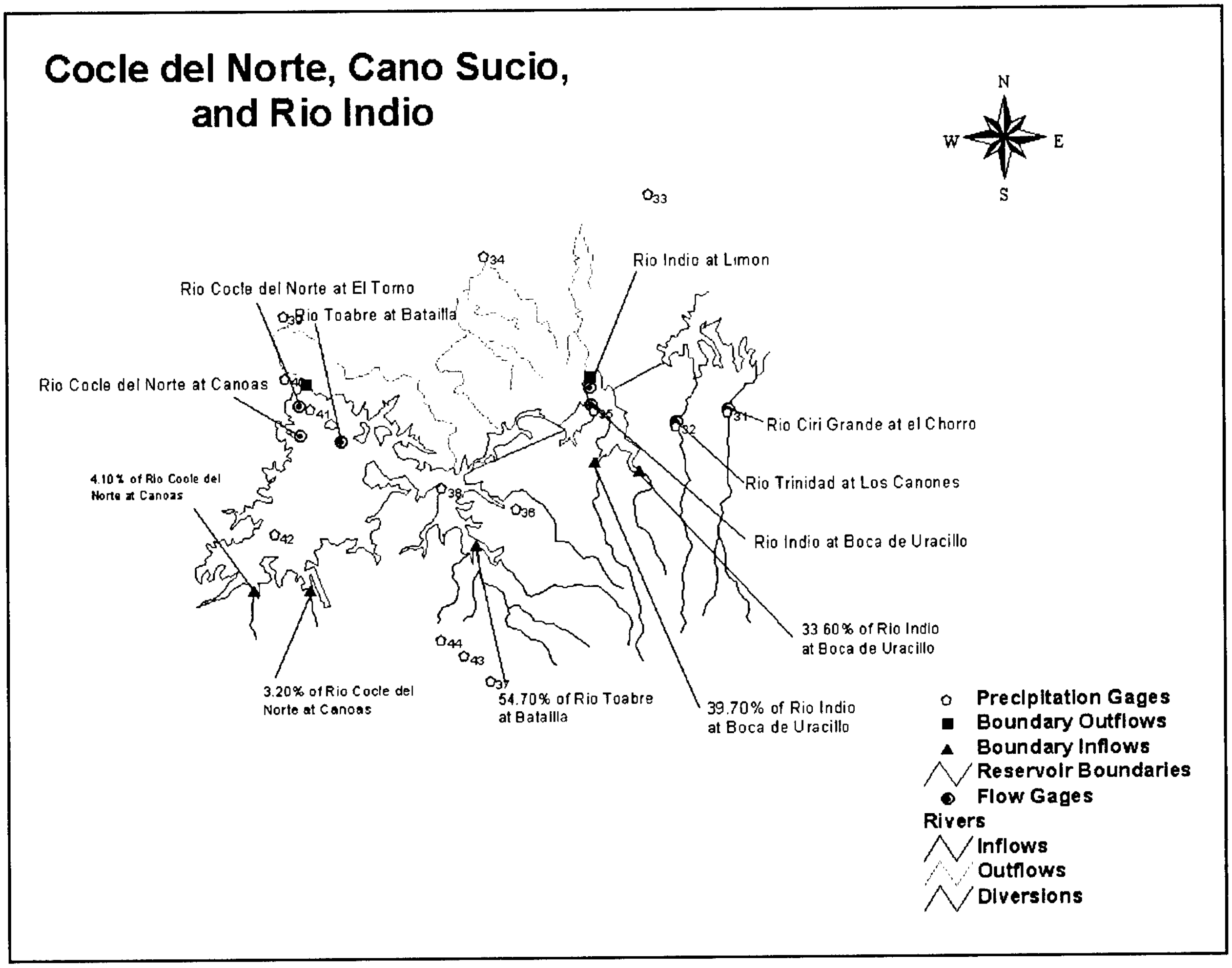

Figure 7-1. Rio Indio, Caño Sucio, and Coclé del Norte reservoirs

Scenarios

Results from HEC-5 reservoir operation simulation studies performed by ACP were obtained and used to develop the scenarios for evaluation of water quality in Rio Indio during operation with and without inter-basin transfers. The HEC-5 output received was for a simulation of the period 1948-1999 using observed monthly inflows and evaporation rates for Gatun Lake and Lake Madden and estimated inflows and evaporation rates for Rio Indio. Water requirements for navigation and Municipal and Industrial (M&I) were based on 171 percent of current demand.

HEC-5 was used by ACP for the purpose of simulating operation of Gatun Lake and Lake Madden with inter-basin transfers from the proposed Rio Indio reservoir. Criteria, developed by ACP for conducting the HEC-5 reservoir operation study, were such that water surface levels of the three reservoirs did not violate minimum or maximum elevations while still supplying adequate quantities of water for operation of Canal locks and meeting M&I demands.

Four sets of conditions were developed for the Rio Indio scenario simulation, Table 7-1. These conditions were selected so that a range of conditions with and without inter-basin transfer could be simulated. Results from simulations 3 and 4 were used to develop water quality characteristics for inter-basin flows from Rio Indio to Gatun Lake. In addition to the Rio Indio simulations, two simulations of Gatun Lake were made. In these simulations, the inter-basin transfer flows were input into Gatun Lake as an additional tributary in the segment corresponding to the location of the tunnel outlet. No water quality changes were assumed to occur in the inter-basin transfers from the time the water was removed from Rio Indio until it entered Gatun Lake. Consequently, the water quality conditions at the tunnel intake in Rio Indio were used as boundary conditions for the tunnel outfall in Gatun Lake.

Table 7-1
Rio Indio Scenarios

Simulation	Description
1	No tunnel transfer flows
	12 m el. intake at dam
2	No tunnel transfer flows
	Multiple intakes at dam (12m, 30m, 50 m el.)
3	Tunnel transfer flows with 32 m el. Intake
	12 m el. intake at dam
4	Tunnel transfer flows with multiple intakes (32, 45, 65m el.)
	12 m el. Intake at dam

The physical characteristics of the proposed Rio Indio reservoir are similar to that of Lake Madden. The Rio Indio reservoir, when operated for water supply, could have large fluctuations in water surface elevation as does Lake Madden currently. Due to these factors, CE-QUAL-W2 was set up for Rio Indio in a manner similar to that used for the Lake Madden application. The same kinetic rates and SOD rates were used for Rio Indio as were used in Lake Madden.

Period

The 50+ years presented in the HEC-5 simulation were too extensive for initial scenario simulations. A shorter interval was selected from this record that represented conditions where there would be periods of inter-basin transfer from Rio Indio to Gatun Lake followed by minimum releases from Rio Indio as it refilled. The period selected was from Jan 1951 to Dec 1954. During this period, Rio Indio reached its maximum elevation during the wet season and drew down approximately 20 m during the dry season when inter-basin transfers were occurring. It was felt that this set of conditions would represent a severe set of conditions in terms of water quality at the beginning of the inter-basin transfers. With the reservoir full, the water flowing into the tunnel intake is farther from the surface. Reaeration effects are less while SOD effects may be greater due to the increased depth. Therefore, all things considered, this should be a worse case than a scenario with lower water levels provided that the same boundary conditions and forcing conditions are used.

Flows

HEC-5 output was used to generate inflow, outflow, and transfer information for Rio Indio and Gatun reservoirs for the scenario simulations. In the case of Rio Indio, the local inflow specified by HEC-5 represented the sum of inflows from all tributaries to Rio Indio. The volumetric evaporation rate was subtracted from this value and the remainder proportioned among the three tributaries to Rio Indio, Table 7-2. In order to simulate conditions without inter-basin transfers it was necessary to combine the tunnel discharge with the Rio Indio spillage and mandatory outflow. As the local inflow included all inflow to the system including rainfall, rainfall was not included in W2 as a separate source. Inflows and outflows for the Rio Indio for the scenarios are shown in Figures 7-2 through 7-6.

Table 7-2
Flow Apportionment for Proposed Rio Indio Reservoir

Tributary	Percent of Net Inflow (Local Inflow – Evaporation)
Rio Indio	39.7%
Rio Uracillo	26.7%
Rio Teria	33.6%

Boundary conditions

Meteorological data. Monthly meteorological data was used in the modeling of Rio Indio, Figures 7-7 to 7-11.

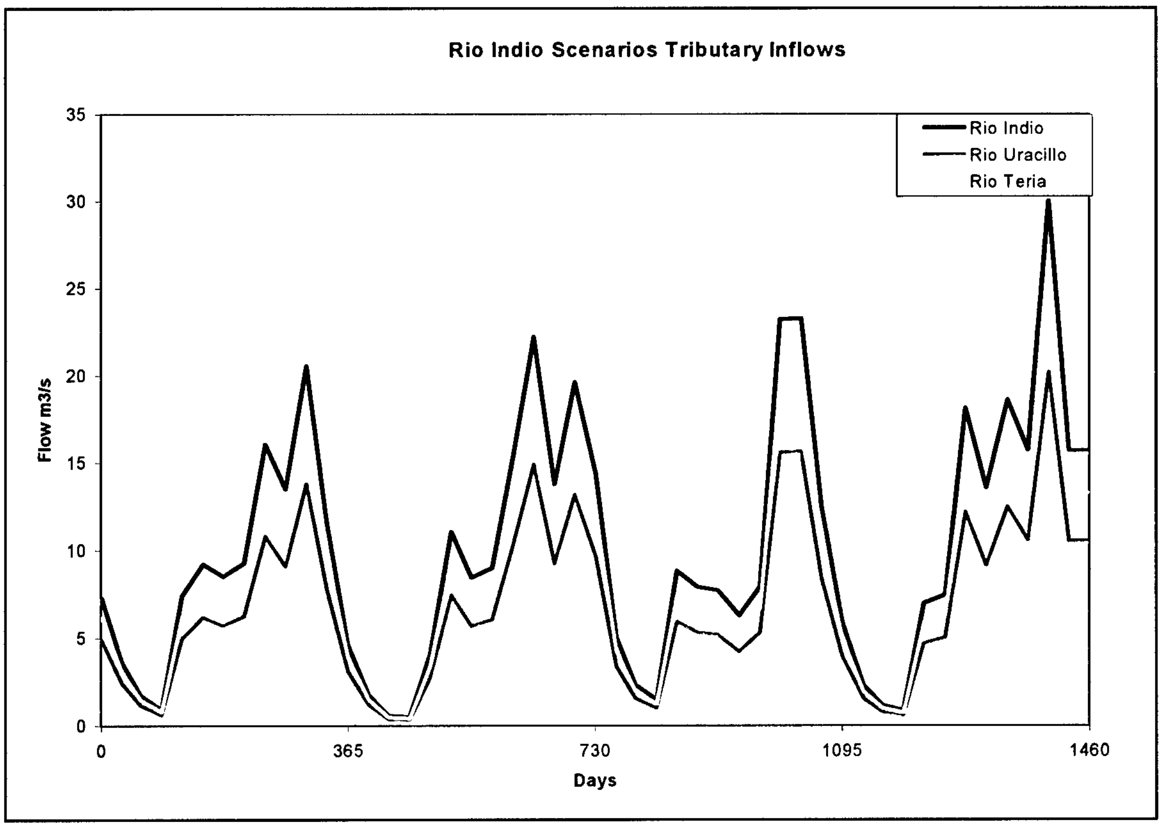

Figure 7-2. Rio Indio scenarios tributary inflows

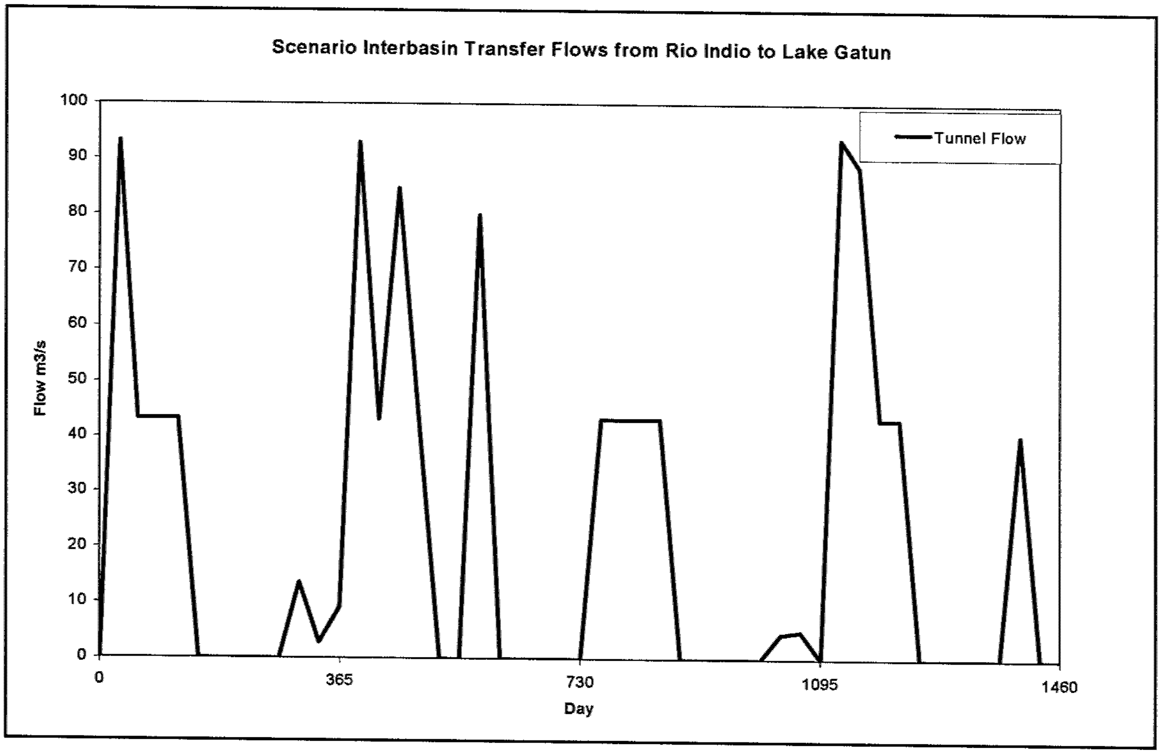

Figure 7-3. Rio Indio inter-basin transfers to Gatun Lake

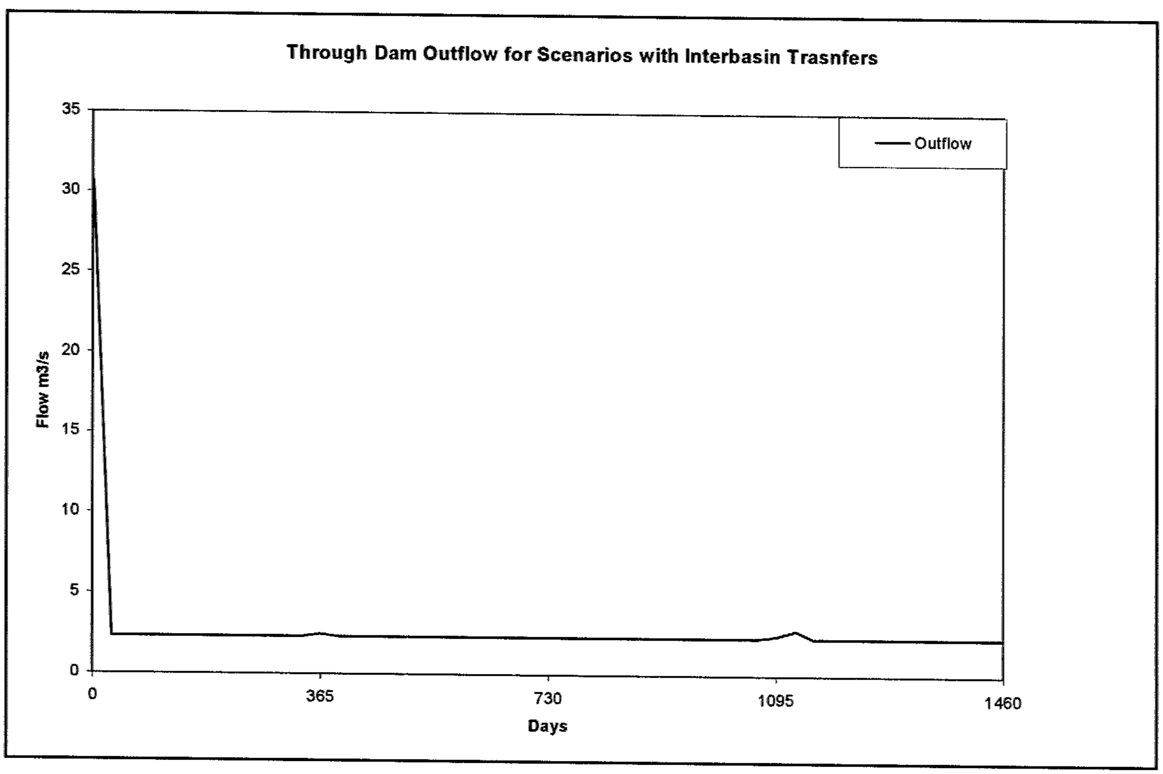

Figure 7-4. Rio Indio downstream discharges

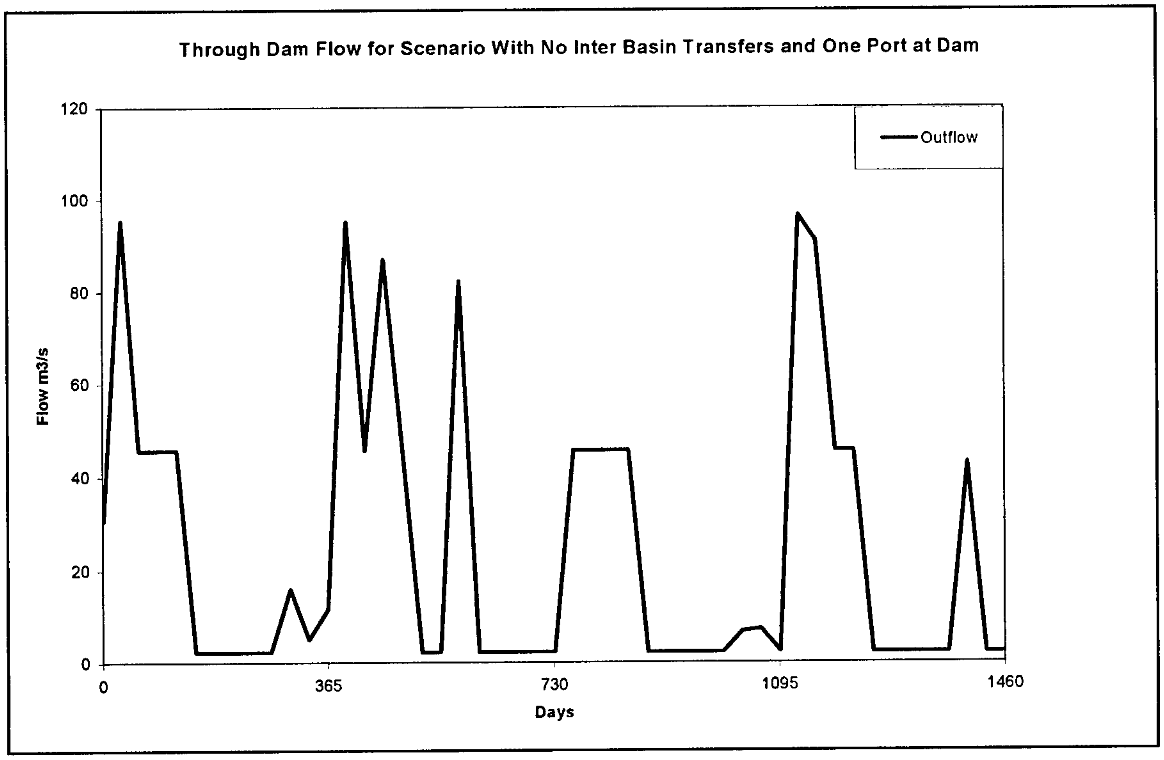

Figure 7-5. Rio Indio downstream discharge with no inter-basin transfer

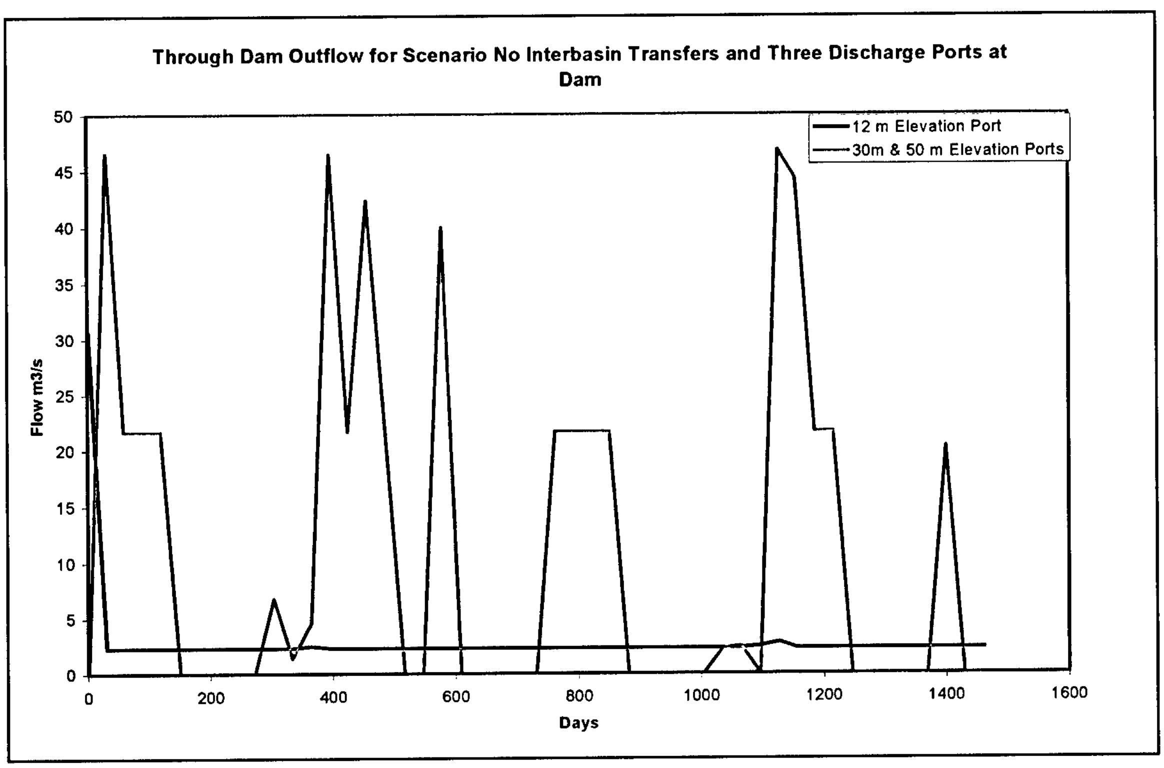

Figure 7-6. Rio Indio downstream discharge using three ports at the dam with no inter-basin transfers

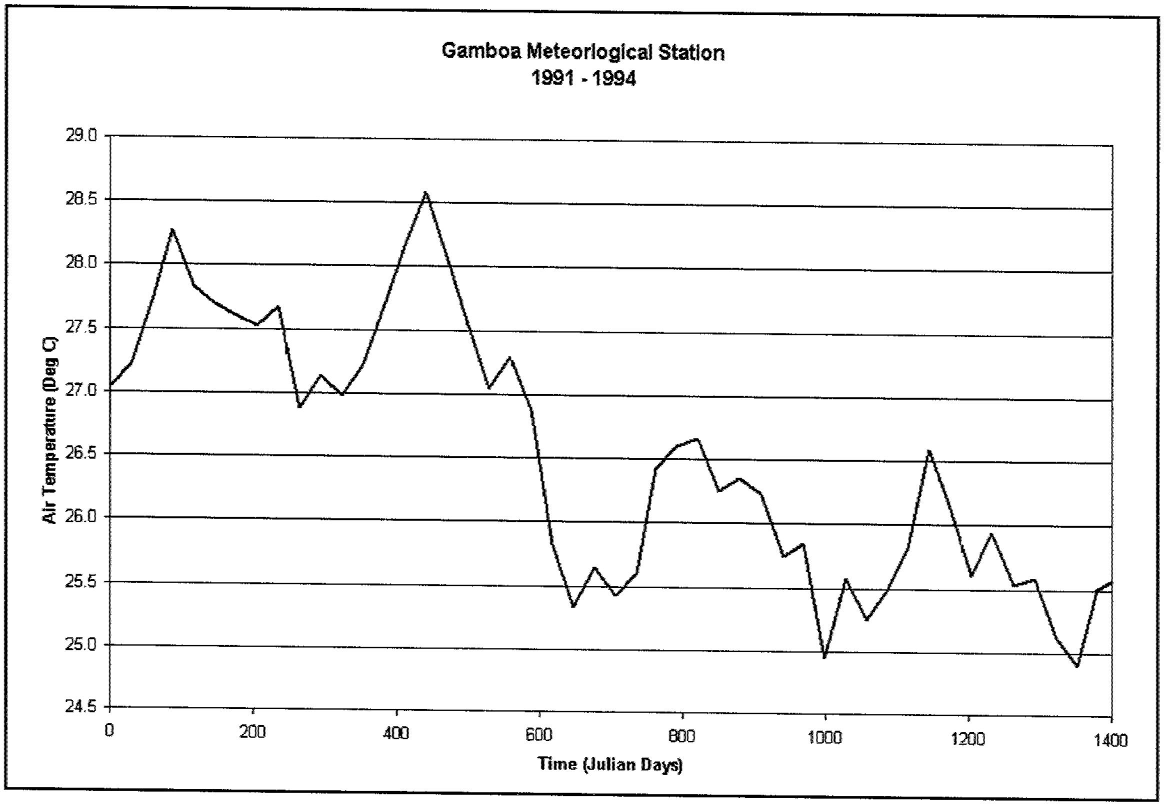

Figure 7-7. Gamboa air temperatures (deg C)

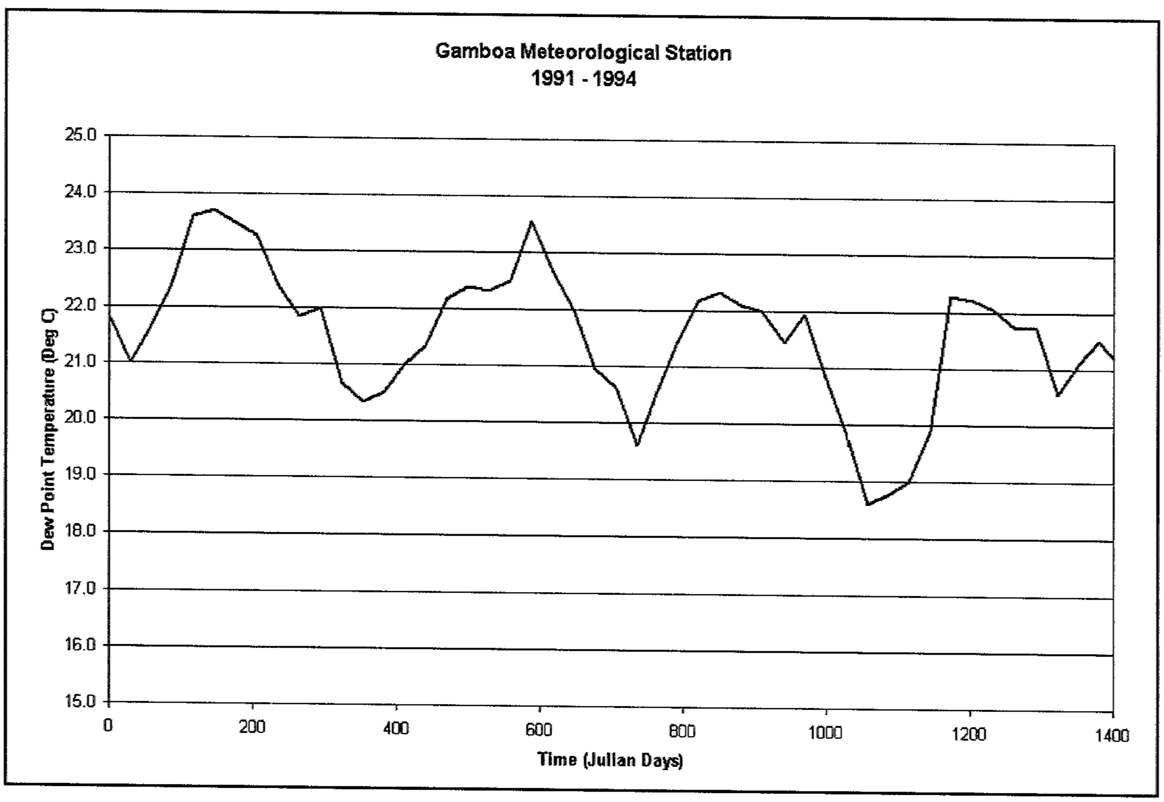

Figure 7-8. Gamboa dew point temperatures (deg C)

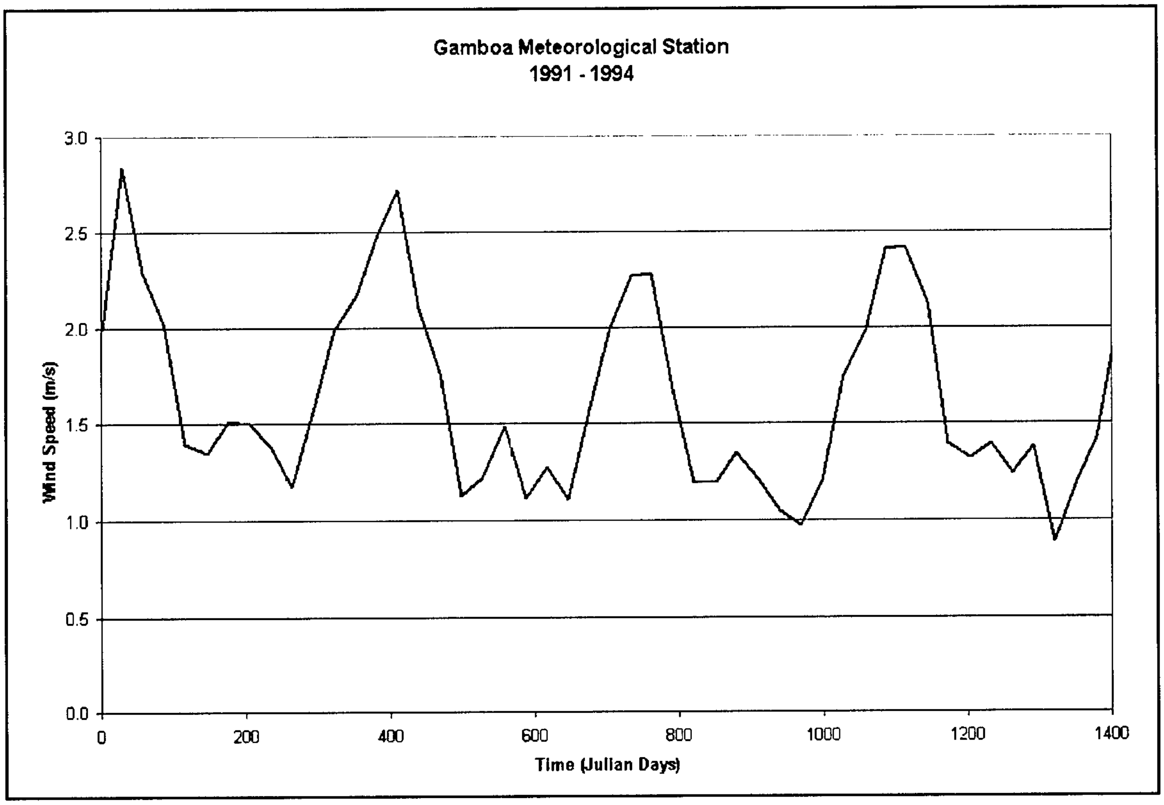

Figure 7-9. Gamboa wind speed (m/s)

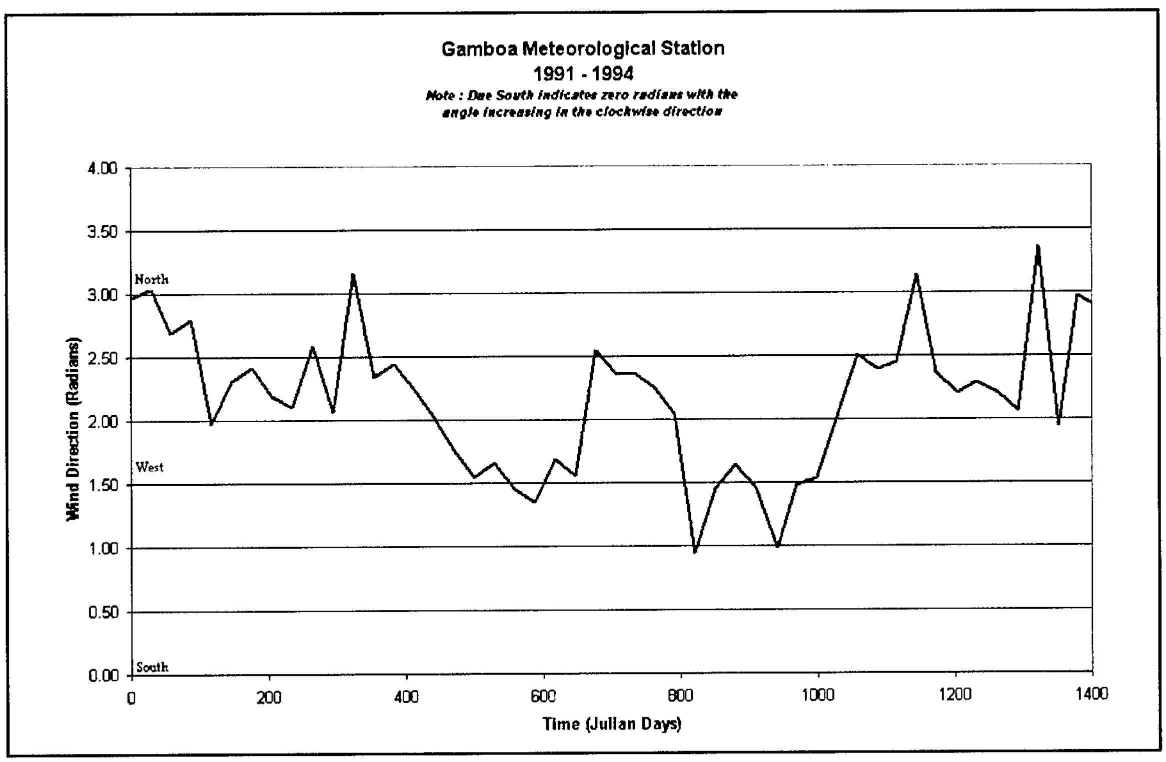

Figure 7-10. Gamboa wind direction (radians)

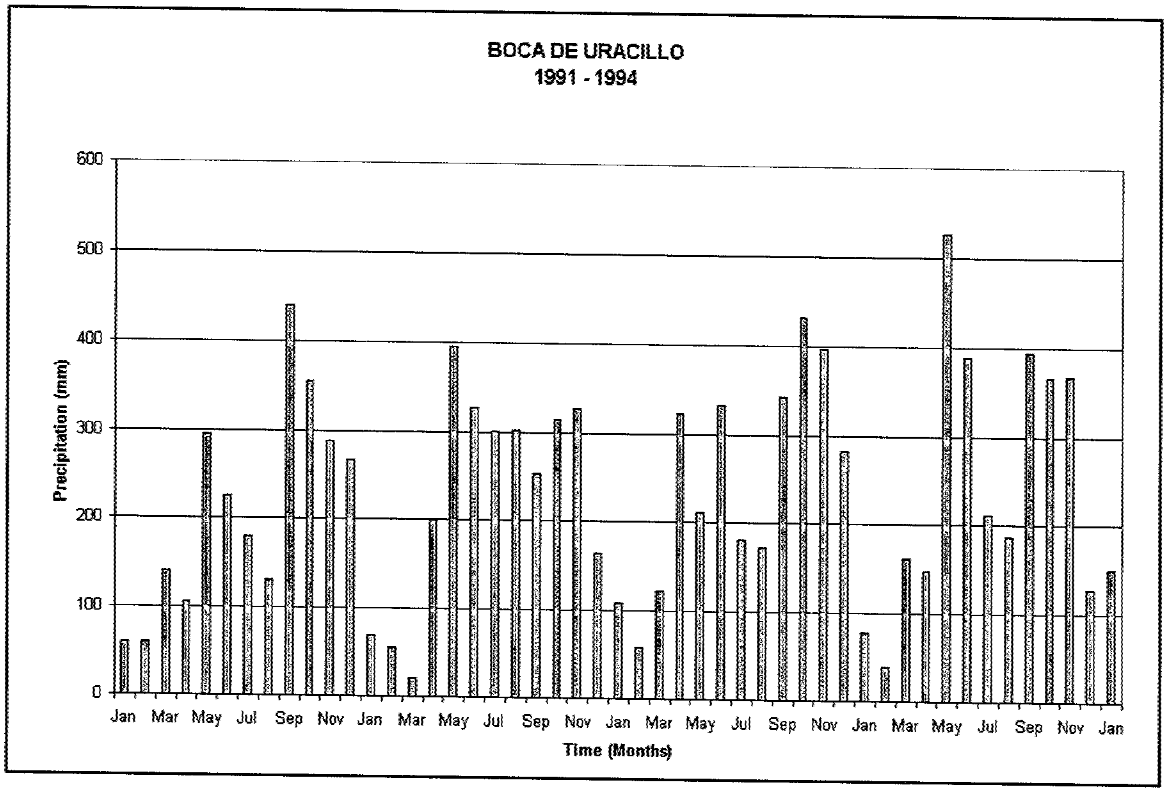

Figure 7-11. Boca de Uracillo precipitation (mm)

Constituents. Boundary concentration values, Table 7-3, were developed for Rio Indio using data collected during the period from Nov 2001 to June 2002. Observed concentration information was combined with corresponding flow information and a flow weighted average concentration developed for each tributary.

Bathymetry

The primary sources used to generate bathymetry for Rio Indio were information provided by MWH. Figure 7-12 describes the branch delineation for Rio Indio. Figure 7-13 describes the segment delineation for Rio Indio. Model bathymetry was compared to volume elevation information generated by MWH and ACP/USACE, Figure 7-14.

Rio Indio results

The four sets of conditions (Table 7-1) tested for Rio Indio resulted in similar water column conditions in each scenario. The water quality constituent of most interest was dissolved oxygen due to its role in the overall "health" of the system. Hypoxic or anoxic conditions (low or no dissolved oxygen) in the reservoir could result in the generation and release of oxygen depleting substances which increase the oxygen demand on the reservoir.

Table 7-3 Rio Indio Tributary Boundary Conditions			
Constituent	**Rio Indio**	**Rio Uracillo**	**Rio Teria**
Total Solids	32.5	7.63	5.0
Fecal Coliform	131.0	447	579.5
Phosphate	0.04	0.04	0.04
Ammonia	0.37	0.42	0.09
Nitrate	0.144	0.075	0.038
Dissolved Oxygen	7.92	7.86	7.66
BOD	2.0	2.0	2.0

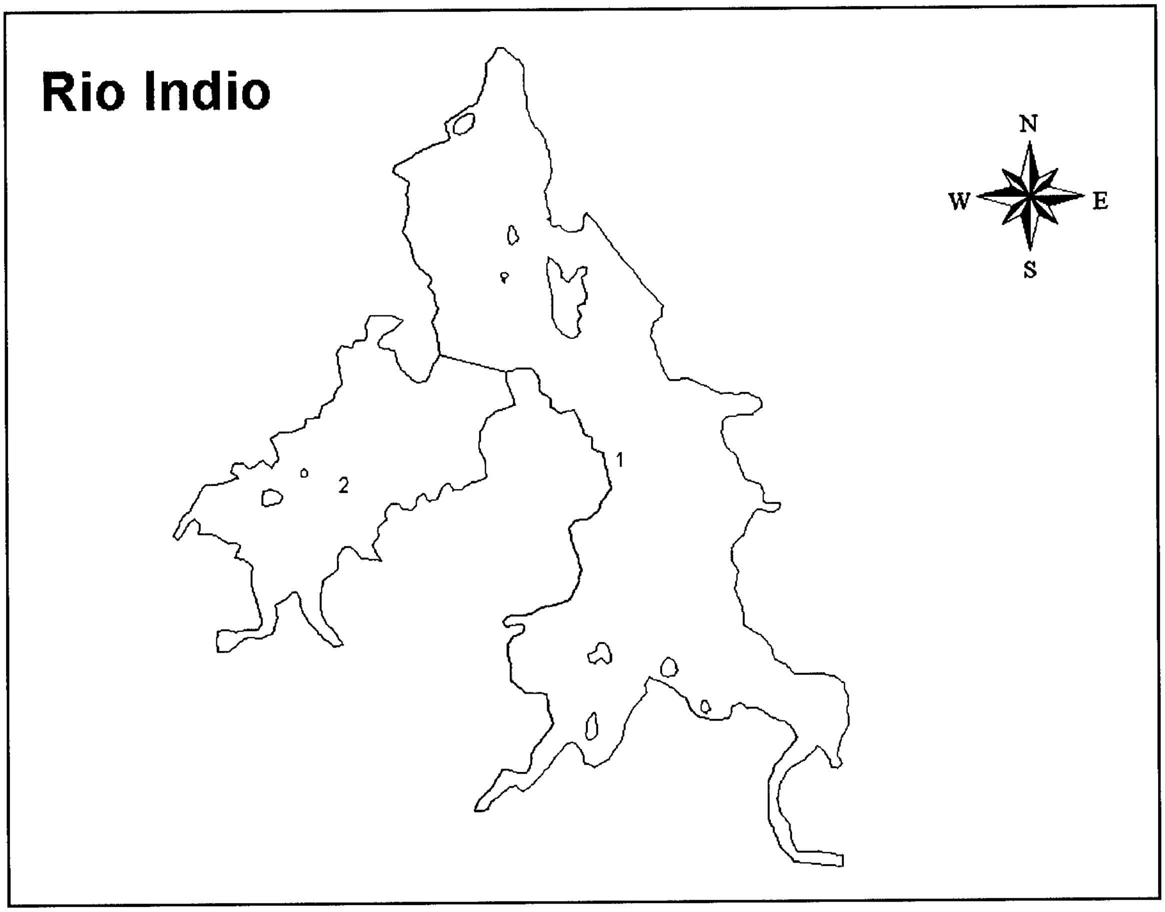

Figure 7-12. Rio Indio branches

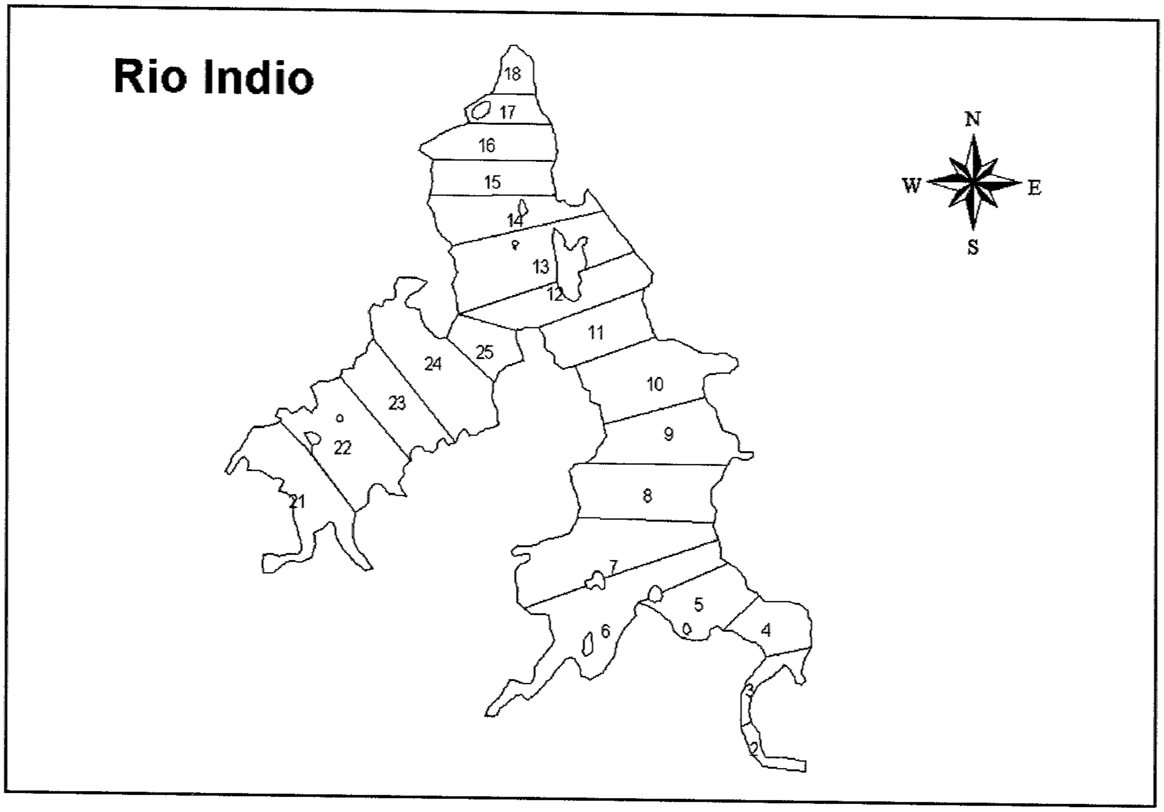

Figure 7-13. Rio Indio segments

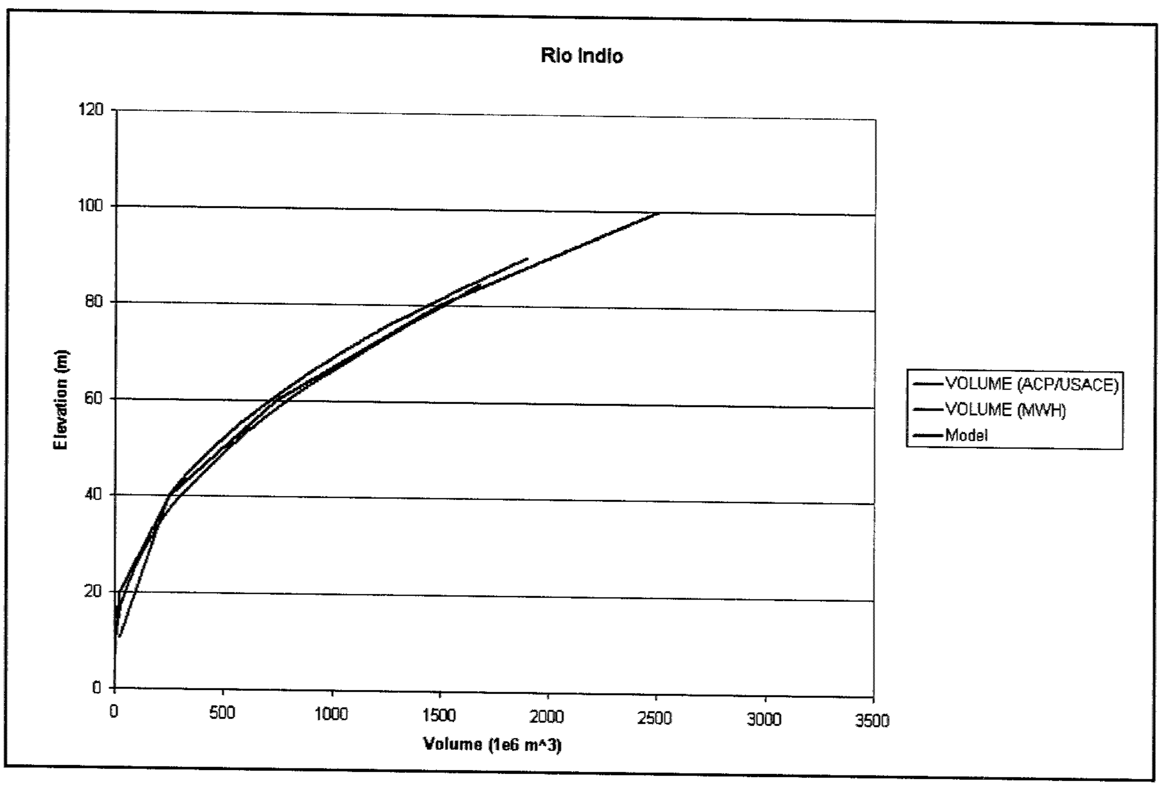

Figure 7-14. Rio Indio volume-elevation curves

Overall, the results of the four scenarios were very similar. Low dissolved oxygen levels were confined to the bottom layers of the reservoir. These low levels were the result of the SOD occurring at the sediment water interface. During conditions where the reservoir was draining, either by downstream flow through dam or inter-basin transfers, dissolved oxygen levels in the lower portions of the reservoir tended to be higher. When the reservoir was filling and only the minimum regulatory flow (82 cfs or 2.32 m^3/s) was being discharge through the dam dissolved oxygen levels in the lower portions of the reservoir decreased until high flow downstream discharges or inter-basin transfers began. As there was no difference in the tributary water quality conditions during this period, the cause for this decrease is attributed to the SOD and the increased residence time (decreased flushing) of the waters in the bottom layers of the reservoir.

The low dissolved oxygen levels indicated for the bottom waters of Rio Indio Reservoir should be an item of concern. Other reservoirs have had similar problems. Low dissolved oxygen levels can result in the release of sediment bound metals which can result in additional water quality problems when the waters are released.

Figure 7-15 describes the location of the Dam Site and the Tunnel Site for the inter-basin water transfer. Figure 7-16 to Figure 7-40 describes the model results, at the Dam Site, for the following parameters: 1) Water Surface elevation; 2) Total Solids; 3) Coliform; 4) Phosphorus; 5) Ammonia; 6) Nitrate-Nitrite; 7) Dissolved Oxygen; 8) CBOD; and 9) Temperature. Figure 7-41 to Figure 7-65 describes the model results, at the Tunnel Site, for the following parameters: 1) Water Surface elevation; 2) Total Solids; 3) Coliform; 4) Phosphorus; 5) Ammonia; 6) Nitrate-Nitrite; 7) Dissolved Oxygen; 8) CBOD; and 9) Temperature.

Shown in Figure 7-66 and 7-67 are longitudinal views of the main branch or Rio Indio reservoir with the locations of the tunnel intakes highlighted. Figure 7-68 through 7-72 contain color shading plots for dissolved oxygen for selected dates during the 4 year simulation for the case with one inlet for the inter-basin transfer tunnel. Figures 7-73 through 7-77 contain similar figures for the case with multiple inlets for the inter-basin transfer tunnel. Arrows on each plot indicate the flow direction and magnitude on those dates. Along with each figure, a hydrograph is included that shows the total inter-basin transfer flow. The red line on the hydrograph corresponds to the time that the shading plot was generated.

The color shading plots for the cases with single and multiple transfer tunnel intakes are very similar. It is evident that during periods of low flow (Figure 7-68) in the Rio Indio reservoir that bottom dissolve oxygen levels drop to near 0 mg/L. Mixing brought about by the inter-basin transfers (Figure 7-69) replenish the dissolved oxygen levels in the bottom waters of the reservoir. This behavior is observed repeatedly throughout the simulation. The reason for the hypoxia and anoxia in the reservoir is the SOD which was estimated at 1 gm O_2/m^2. Lower values of SOD would result in less anoxia while higher values would create more. While there is anoxia, it does not extend to the level of the inter-basin transfer tunnel in these scenarios and is thus not passed to Gatun Lake.

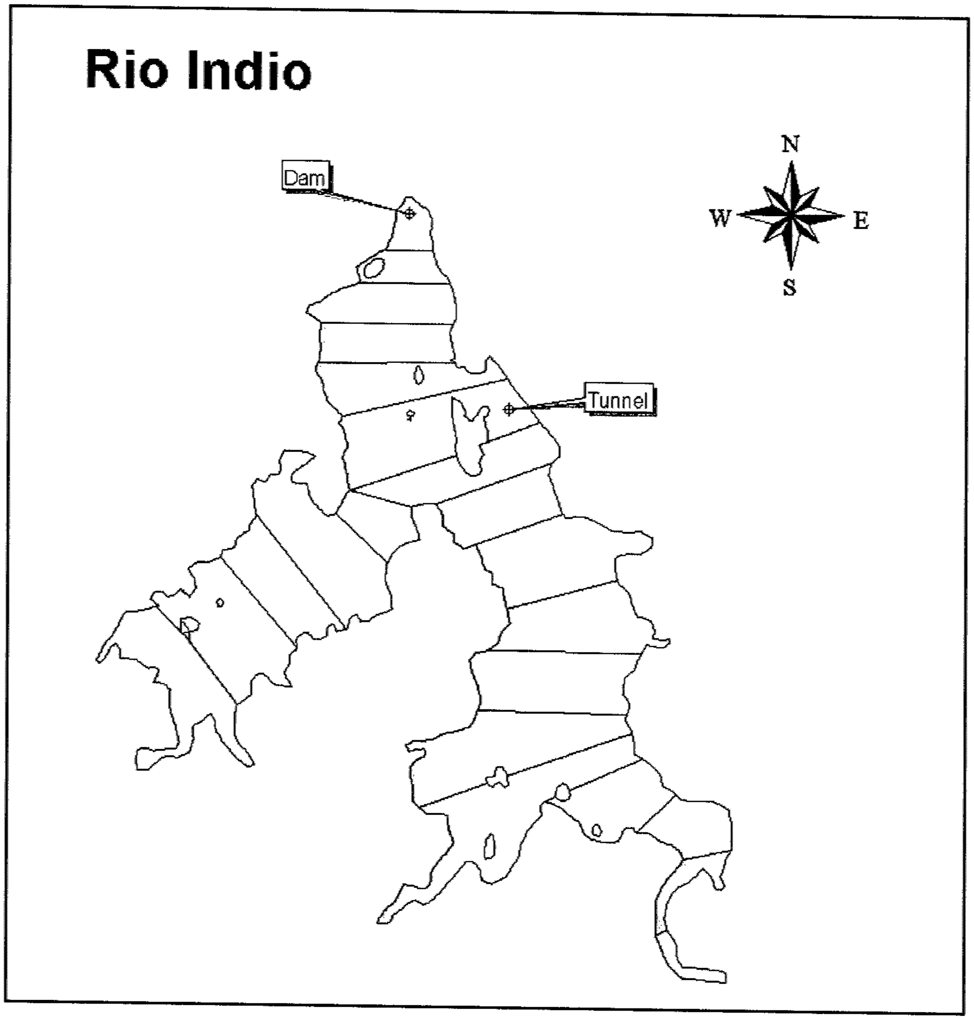

Figure 7-15. Locations from which model results were compared

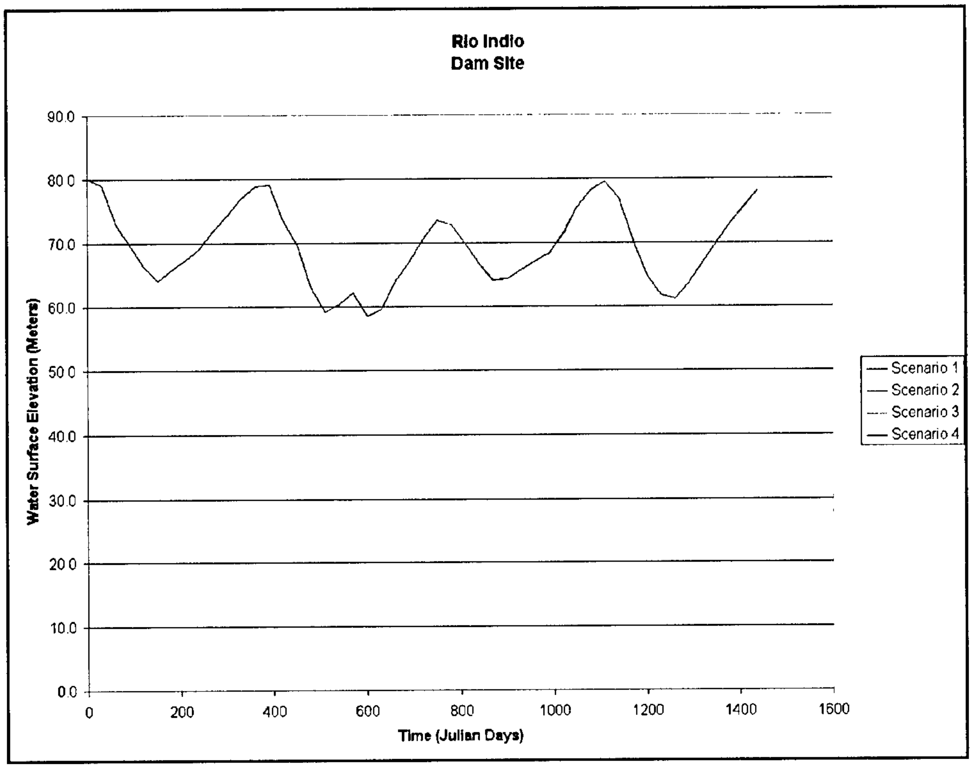

Figure 7-16. WSEL at dam site

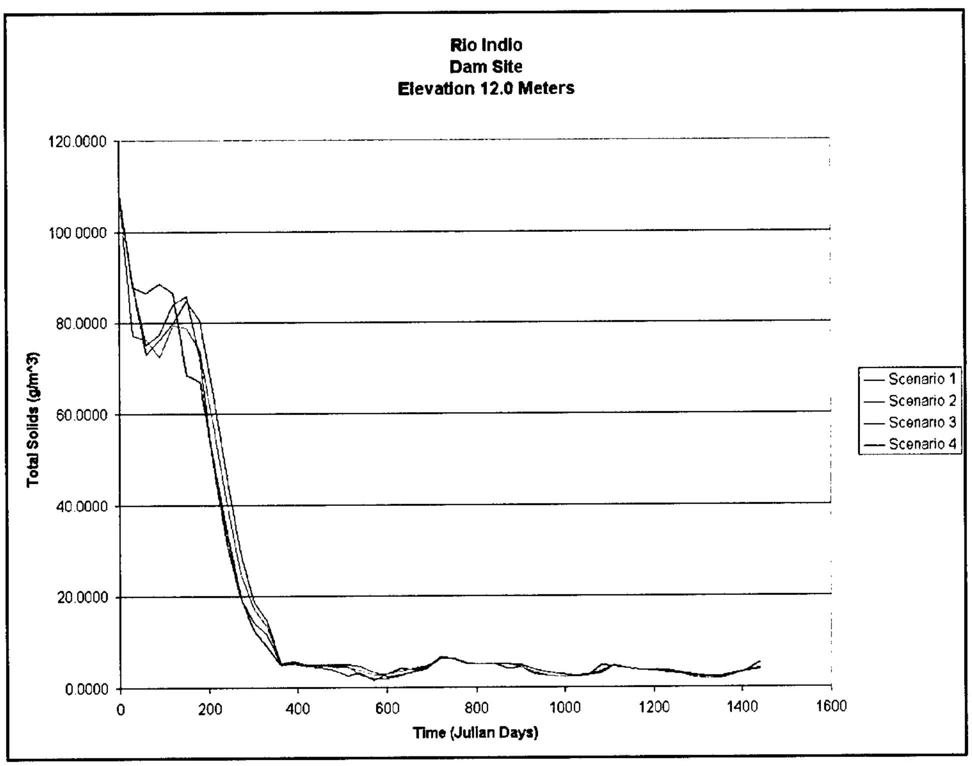

Figure 7-17. Total solids, elevation 12.0, at dam site

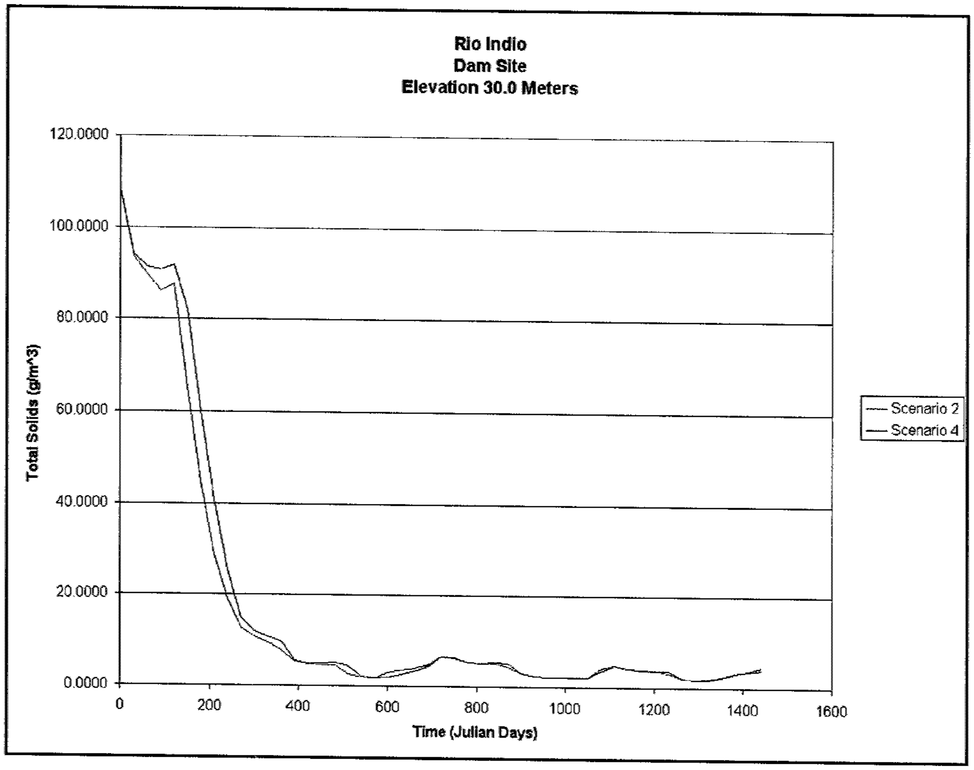

Figure 7-18. Total solids, elevation 30.0, at dam site

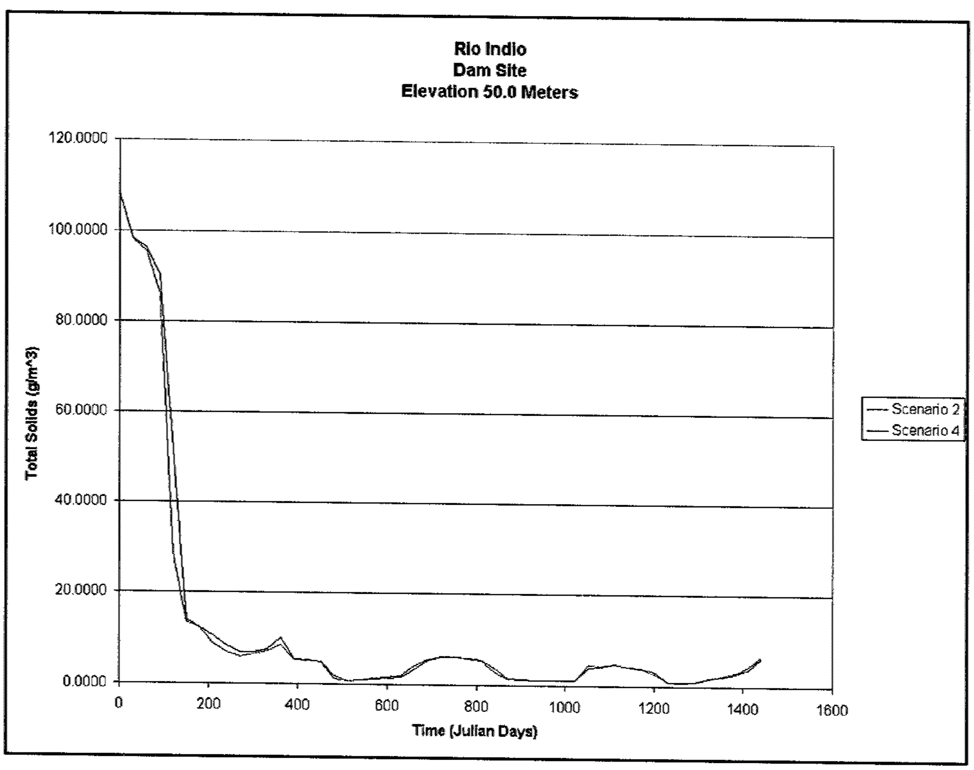

Figure 7-19. Total solids, elevation 50.0, at dam site

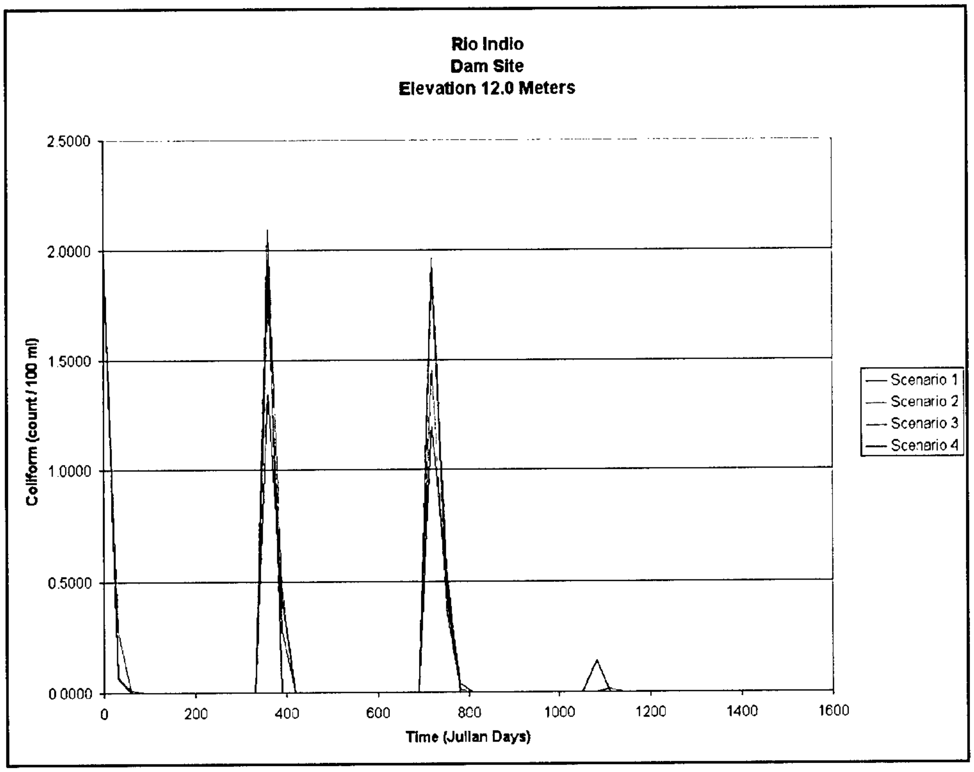

Figure 7-20. Coliform, elevation 12.0, at dam site

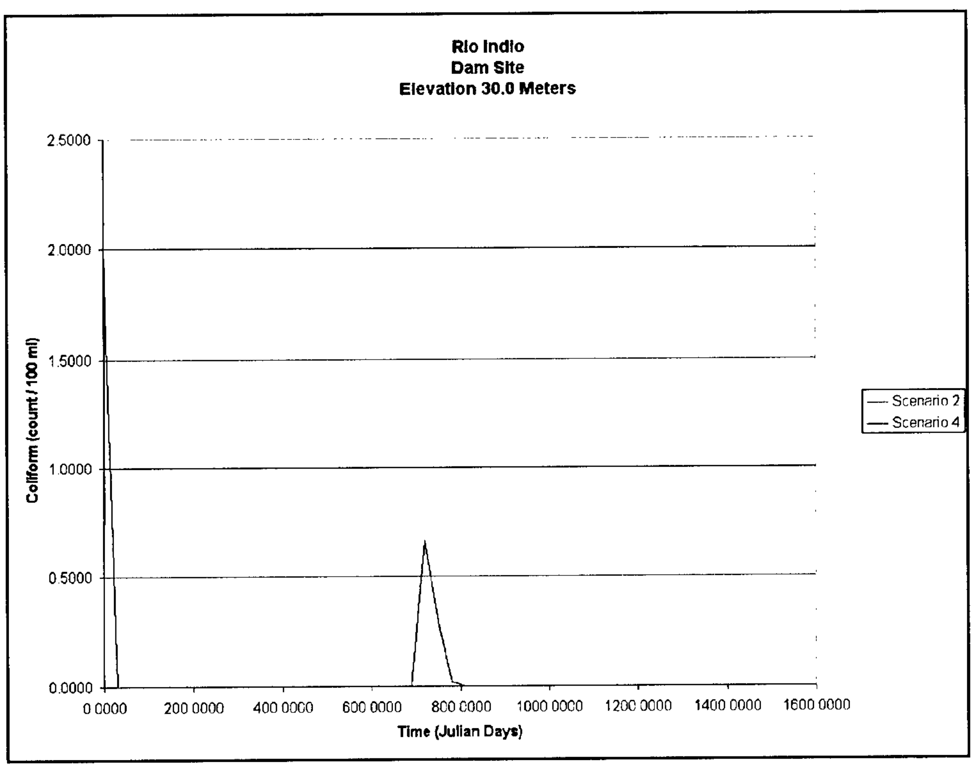

Figure 7-21. Coliform, elevation 30.0, at dam site

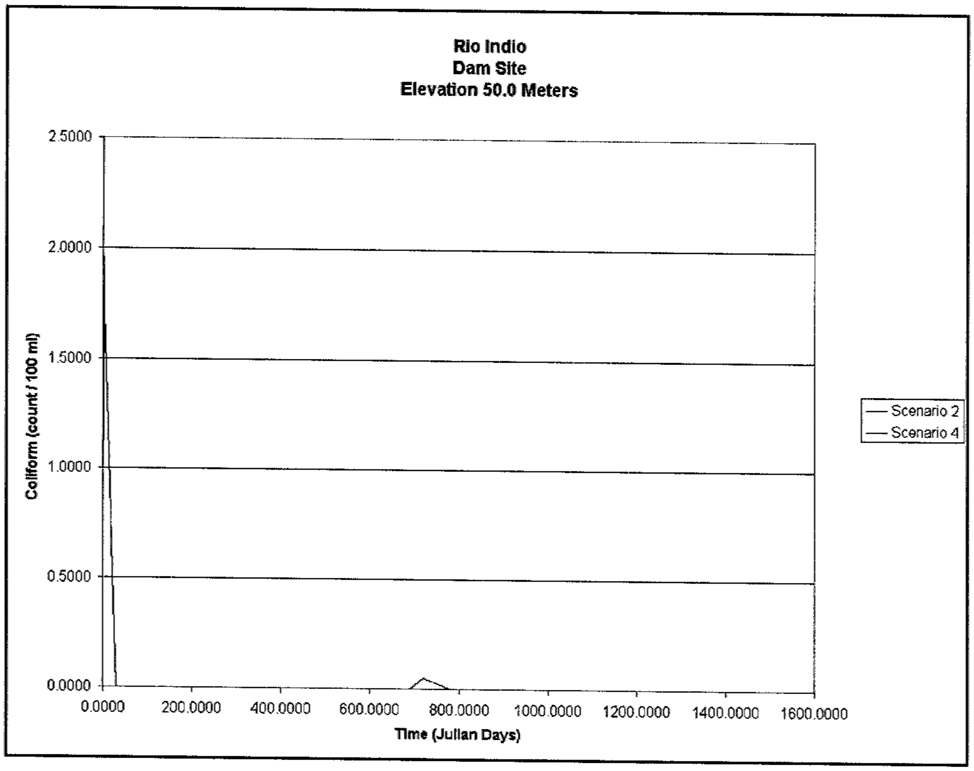

Figure 7-22. Coliform, elevation 50.0, at dam site

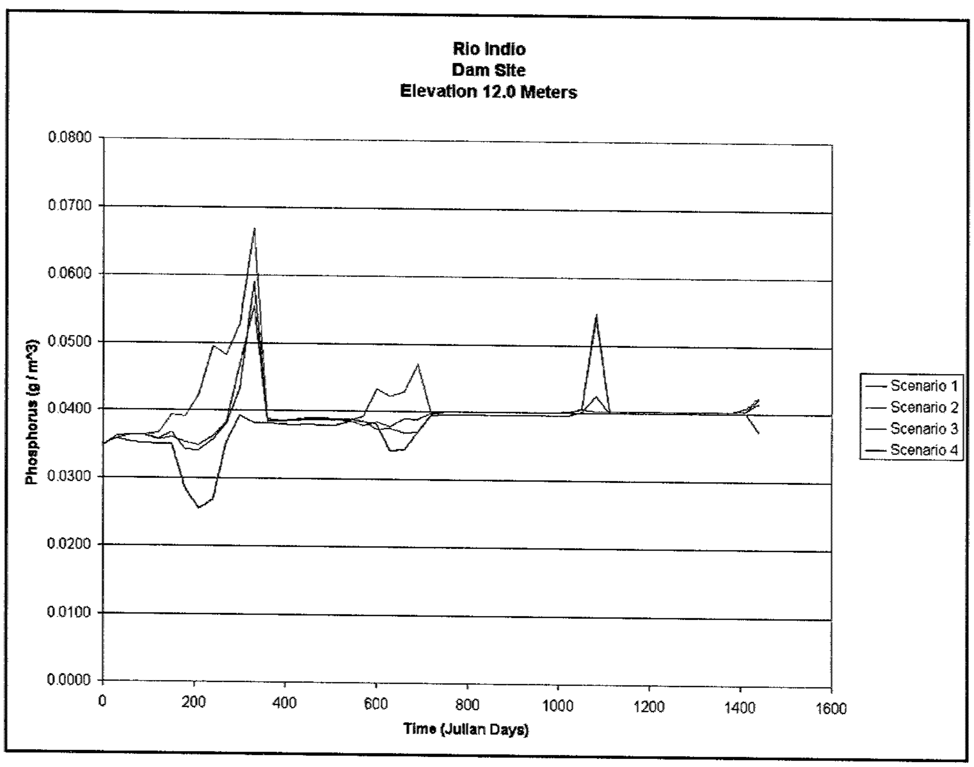

Figure 7-23. Phosphorus, elevation 12.0, at dam site

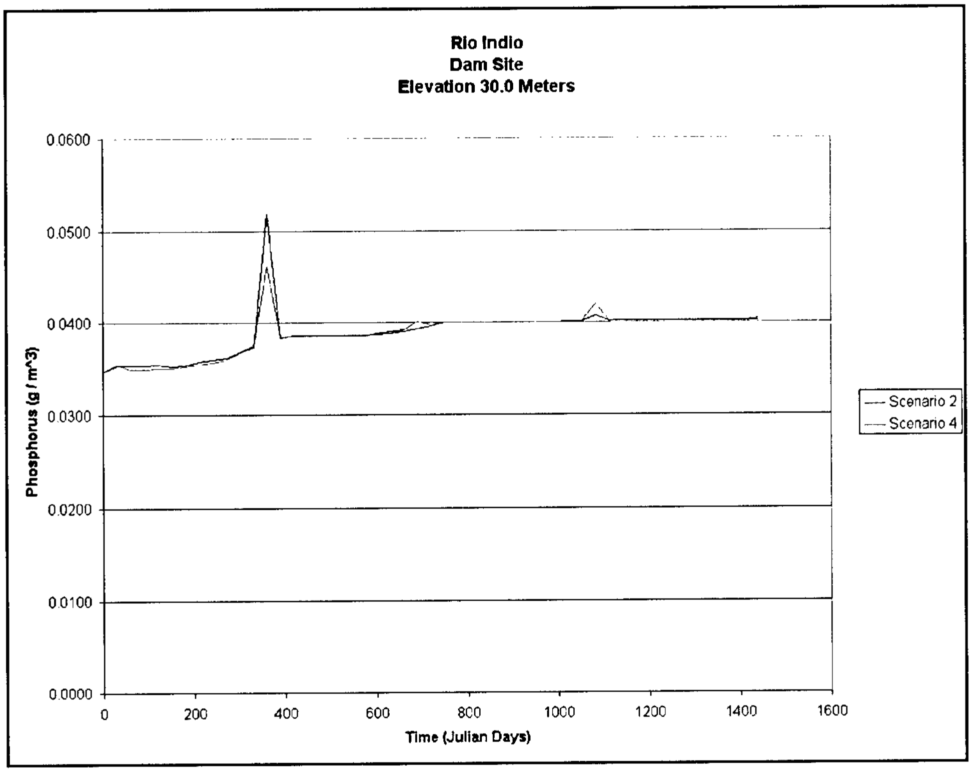

Figure 7-24. Phosphorus, elevation 30.0, at dam site

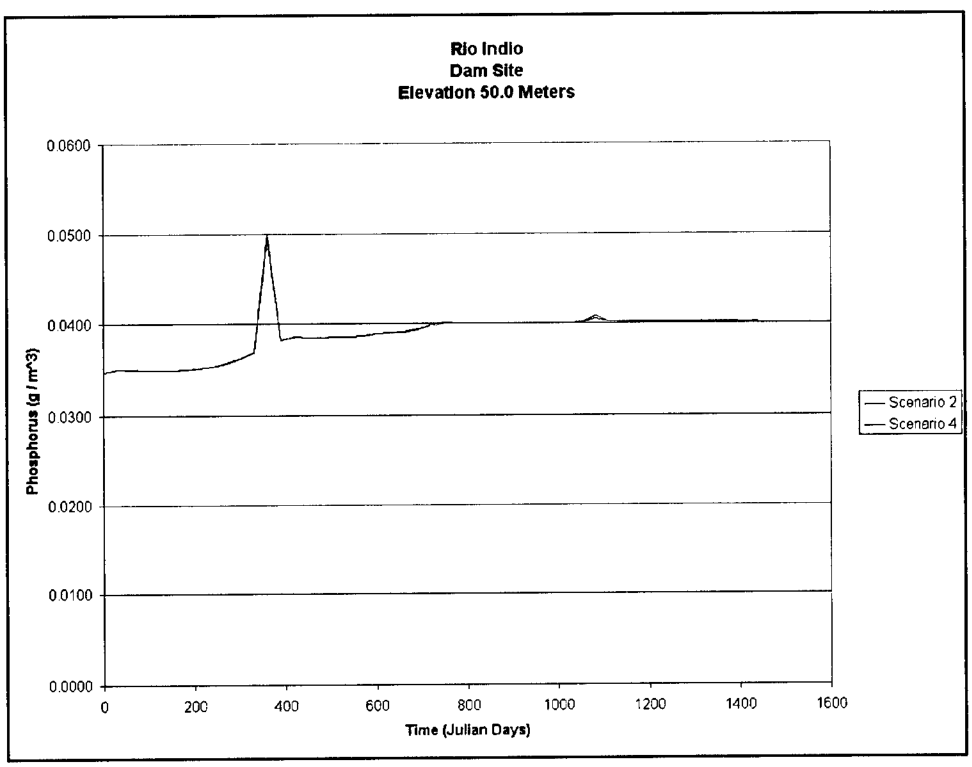

Figure 7-25. Phosphorus, elevation 50.0, at dam site

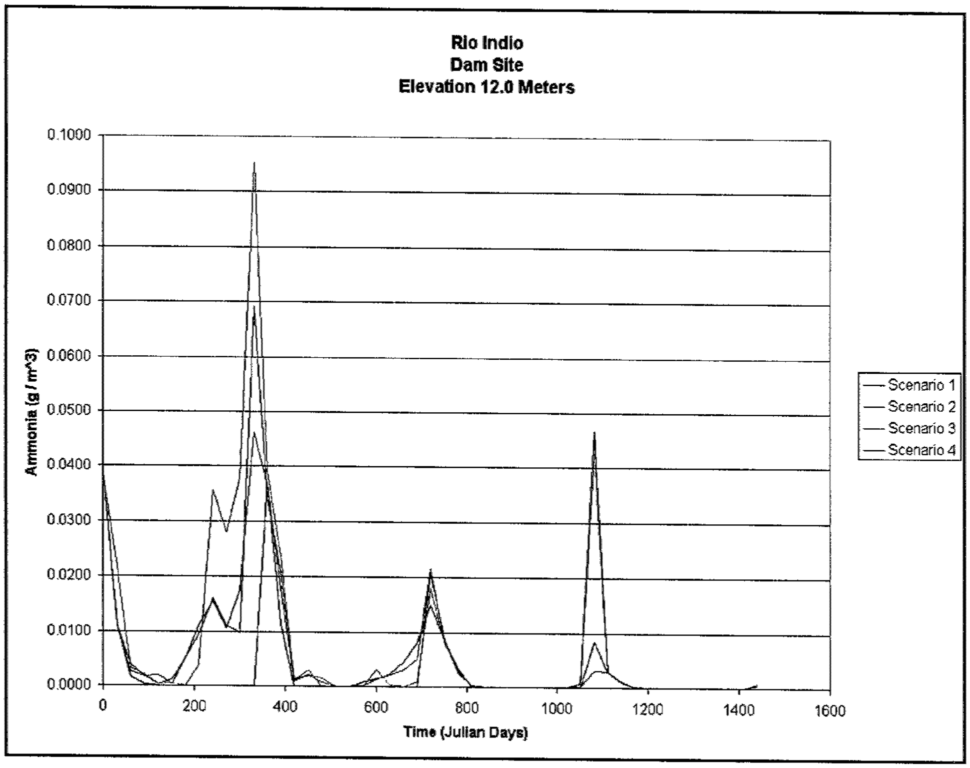

Figure 7-26. Ammonia, elevation 12.0, at dam site

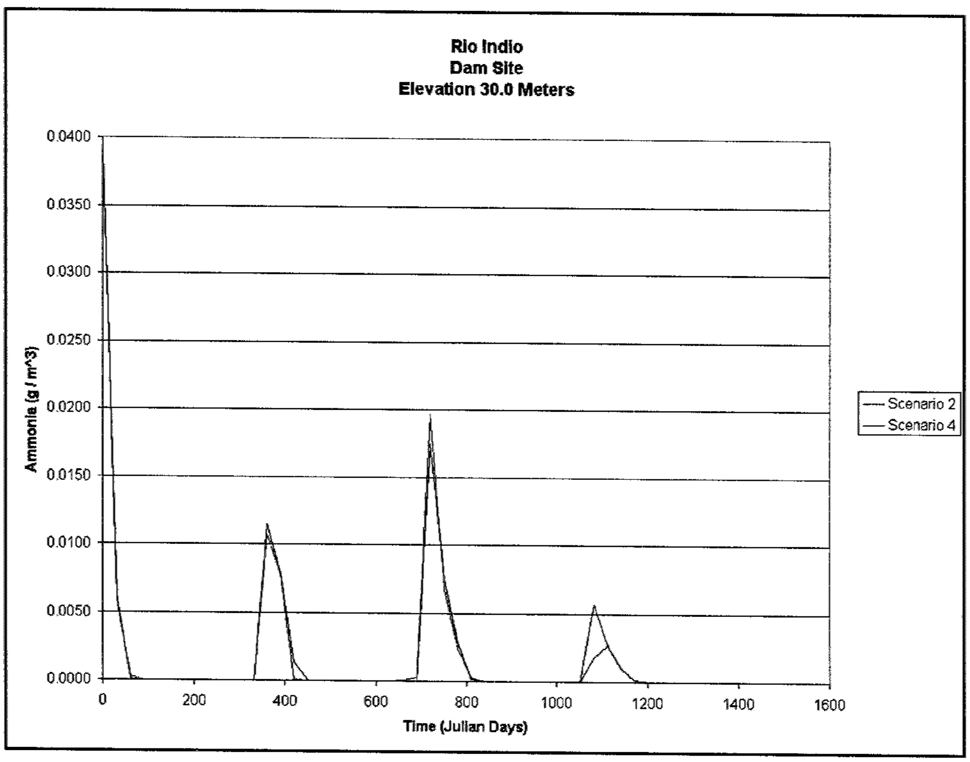

Figure 7-27. Ammonia, elevation 30.0, at dam site

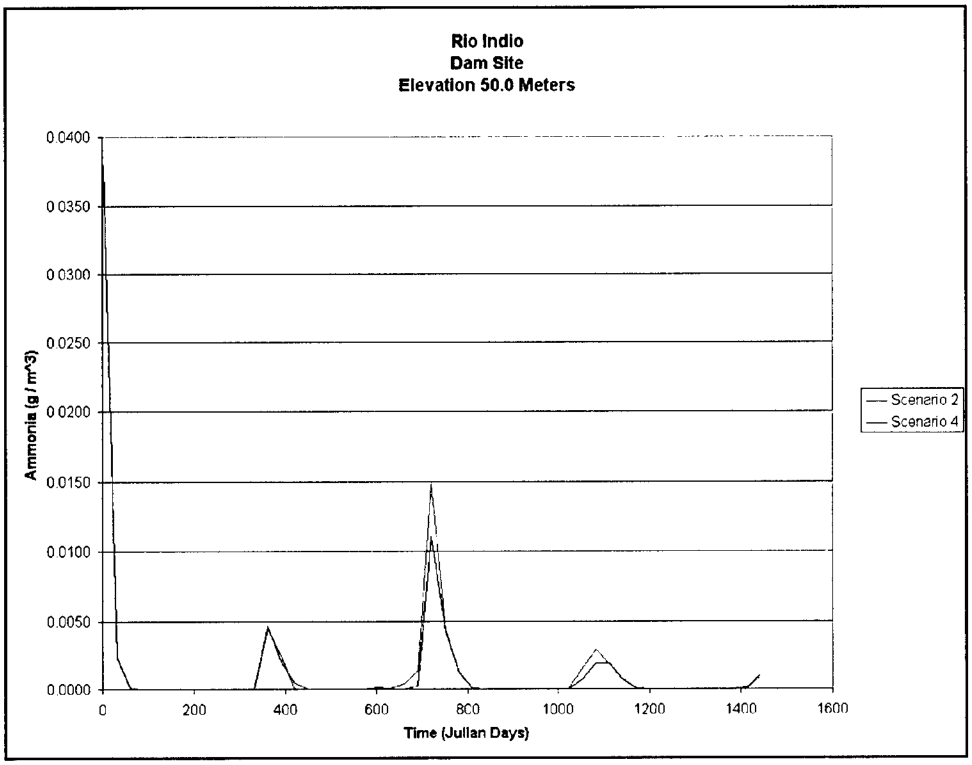

Figure 7-28. Ammonia, elevation 50.0, at dam site

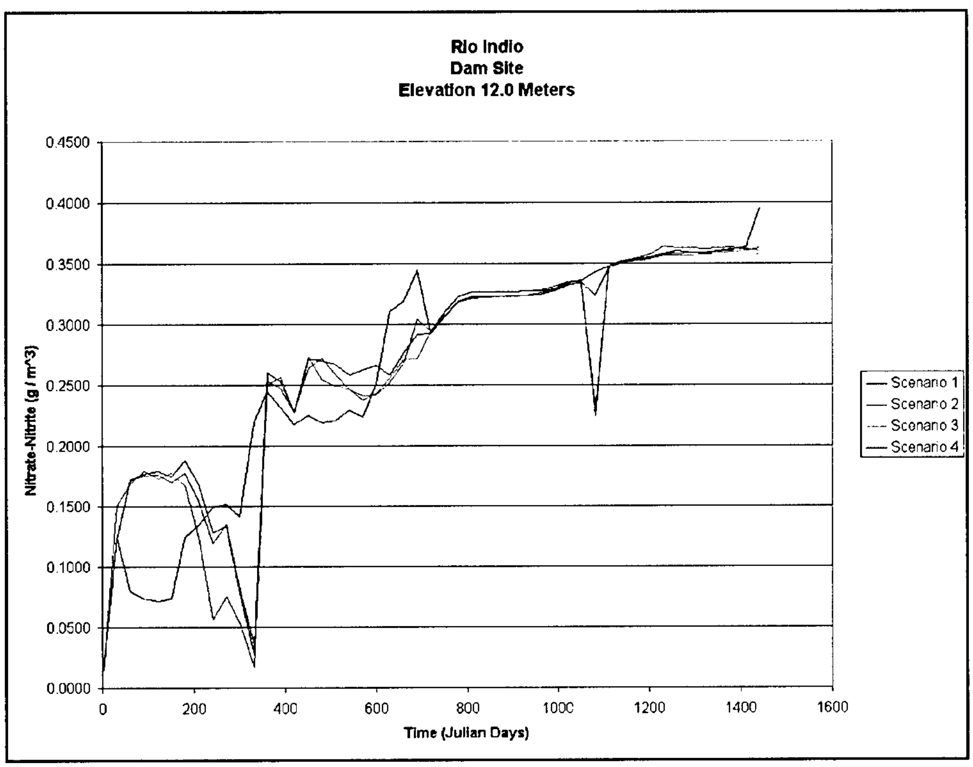

Figure 7-29. Nitrate-nitrite, elevation 12.0, at dam site

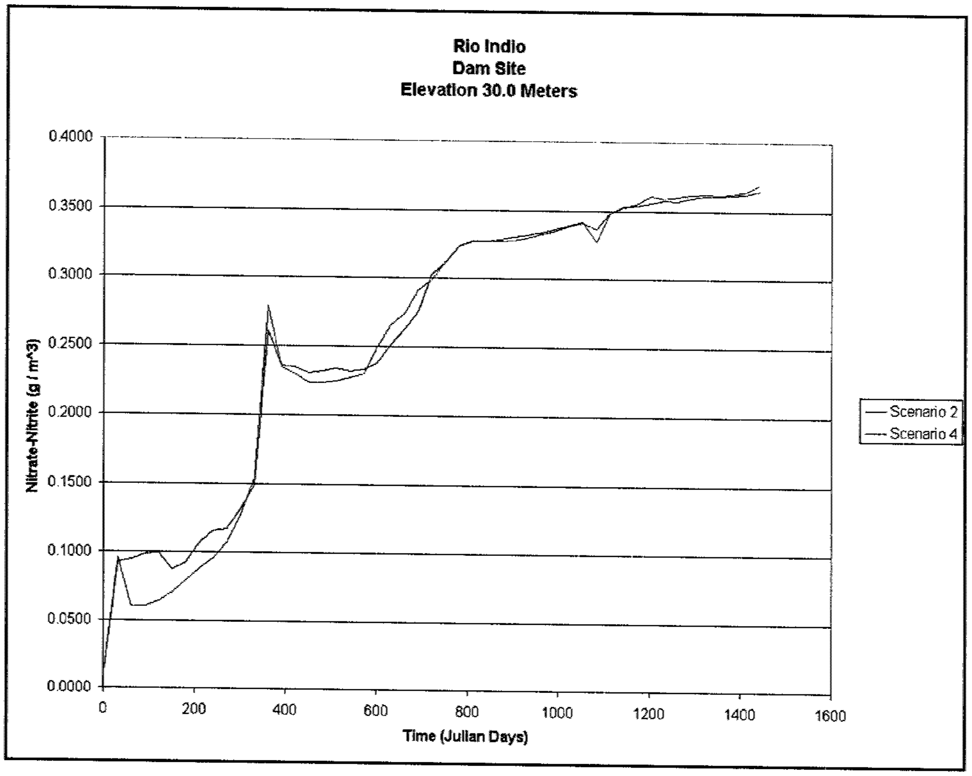

Figure 7-30. Nitrate-nitrite, elevation 30.0, at dam site

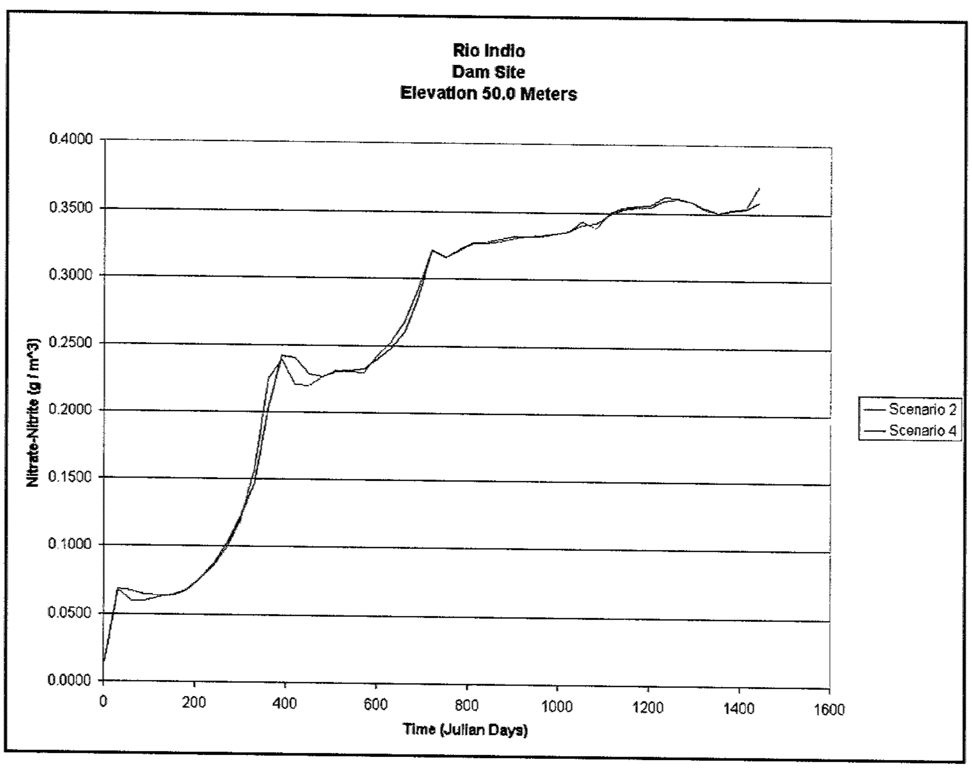

Figure 7-31. Nitrate-nitrite, elevation 50.0, at dam site

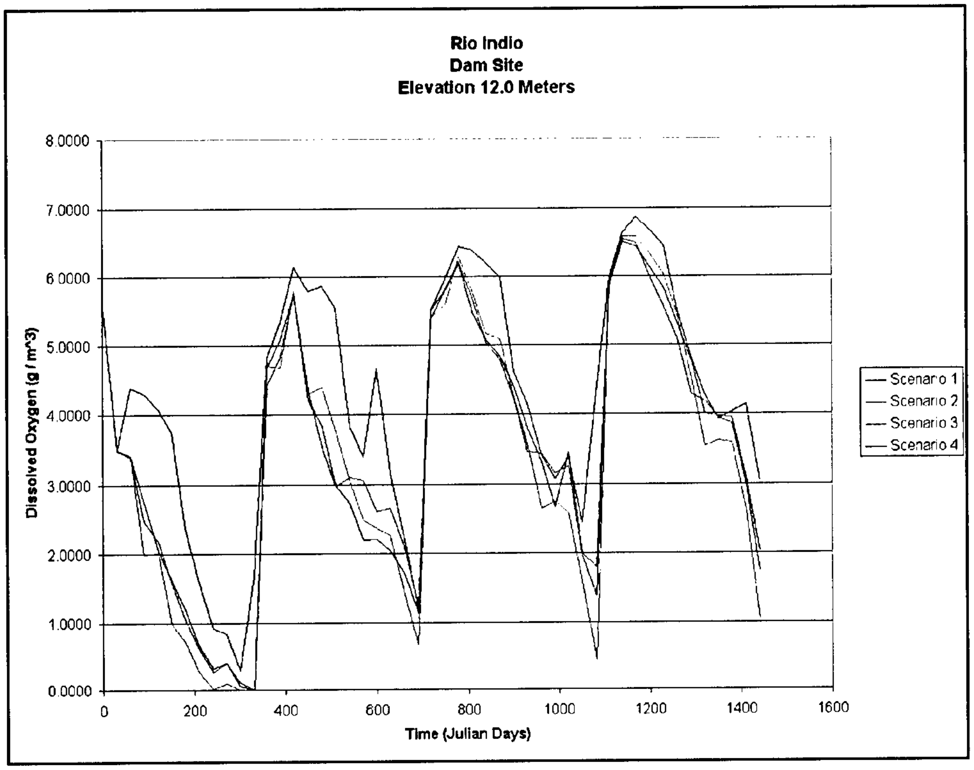

Figure 7-32. Dissolved oxygen, elevation 12.0, at dam site

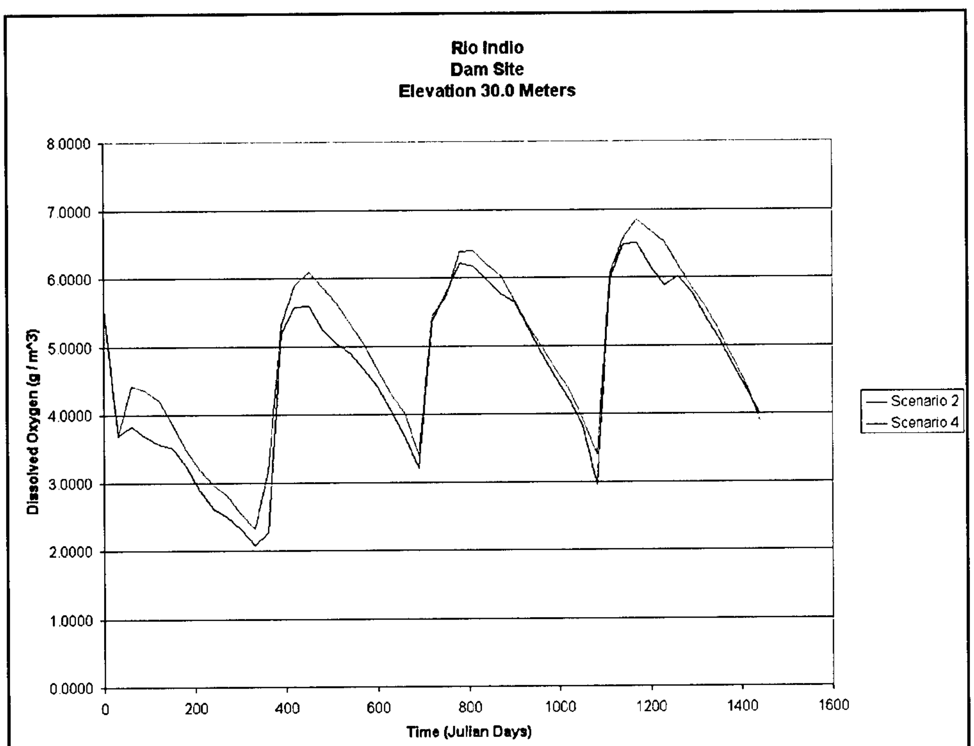

Figure 7-33. Dissolved oxygen, elevation 30.0, at dam site

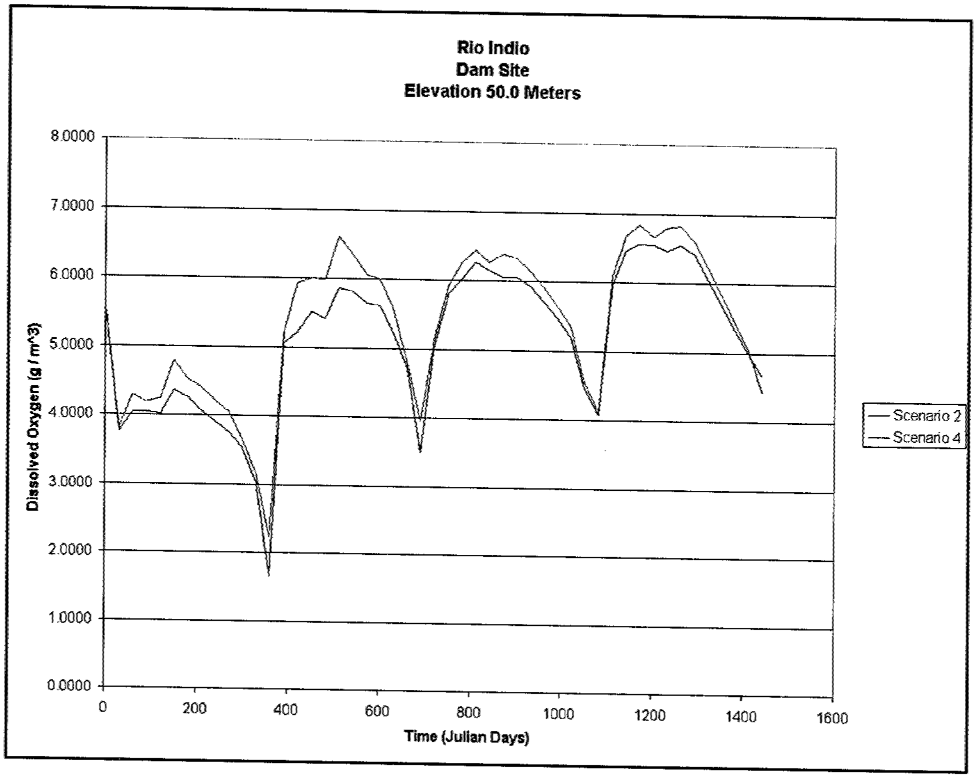

Figure 7-34. Dissolved oxygen, elevation 50.0, at dam site

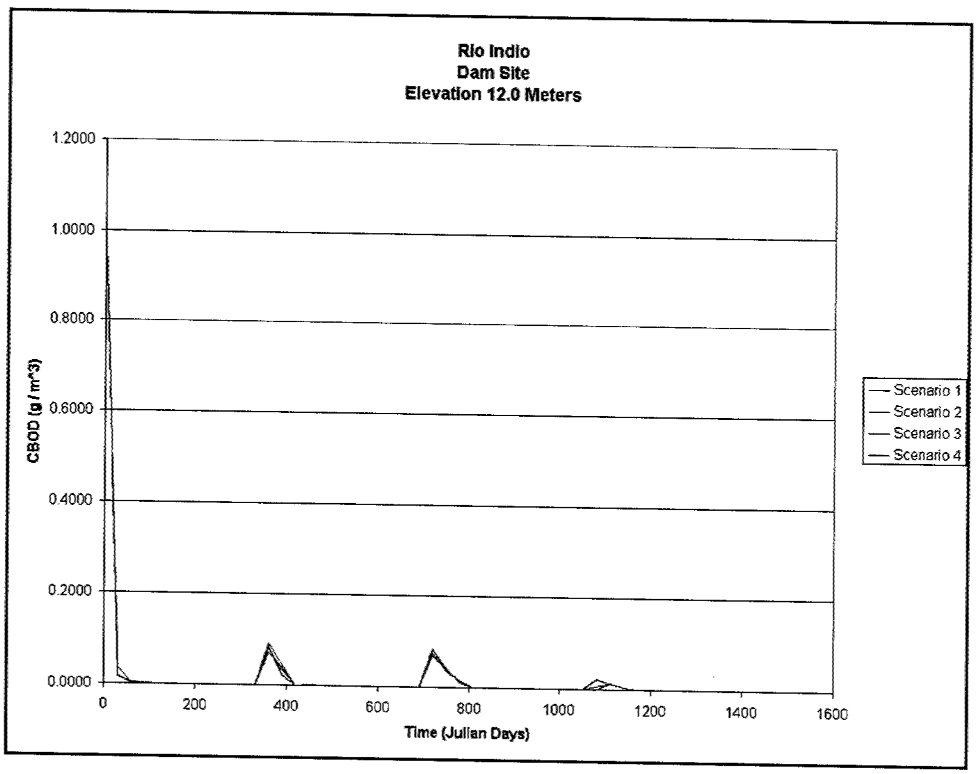

Figure 7-35. CBOD, elevation 12.0, at dam site

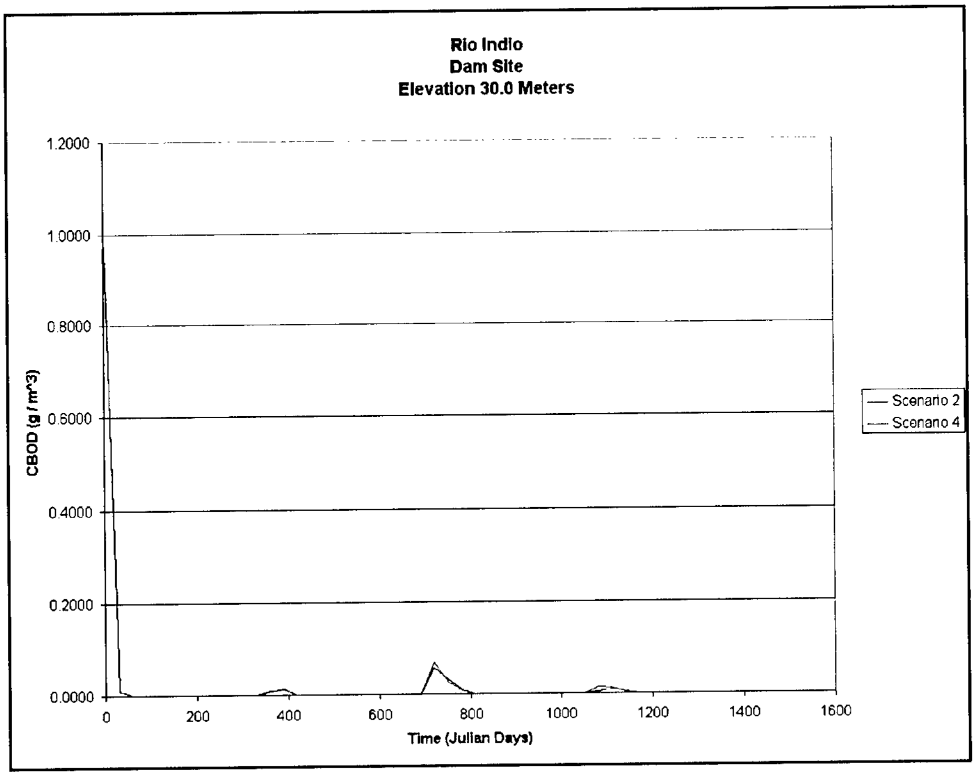

Figure 7-36. CBOD, elevation 30.0, at dam site

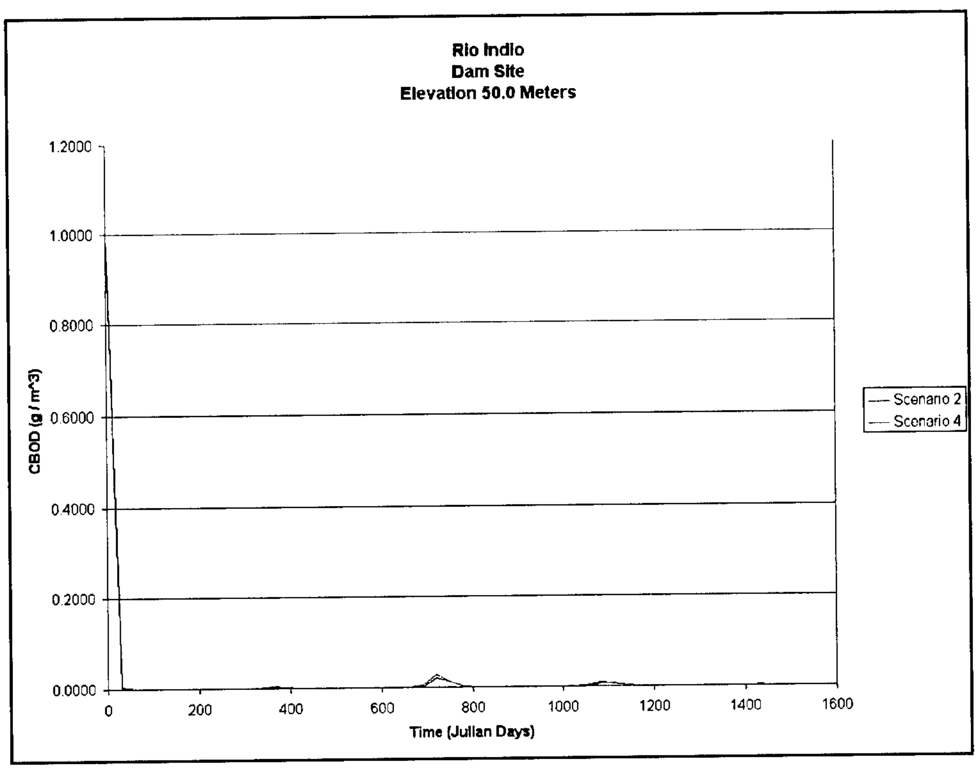

Figure 7-37. CBOD, elevation 50.0, at dam site

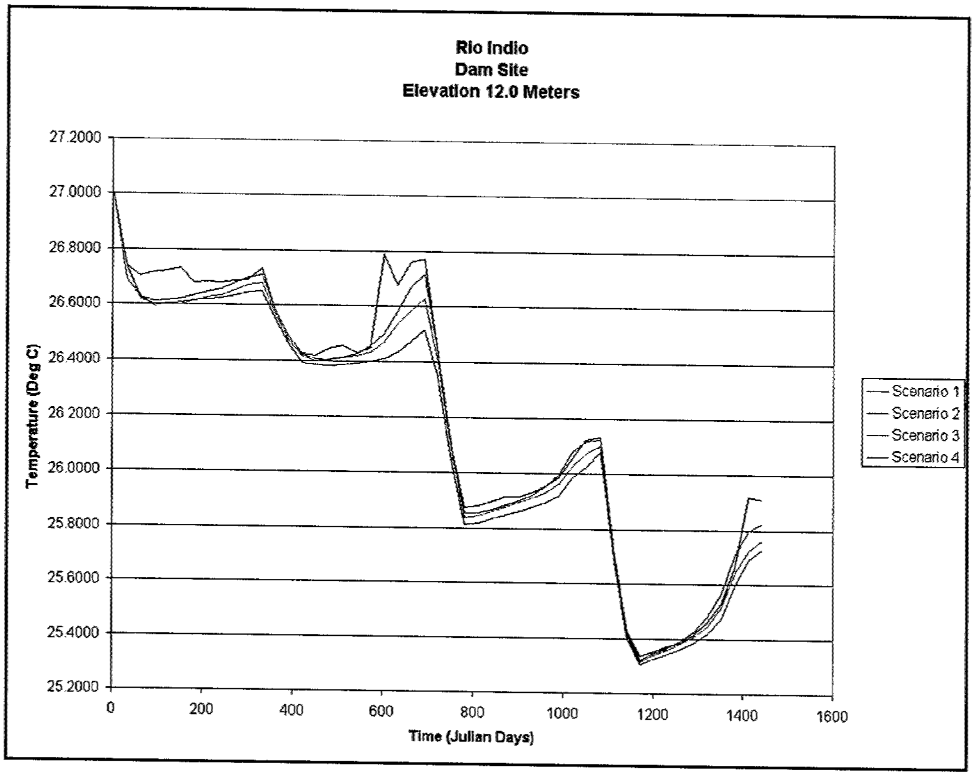

Figure 7-38. Temperature, elevation 12.0, at dam site

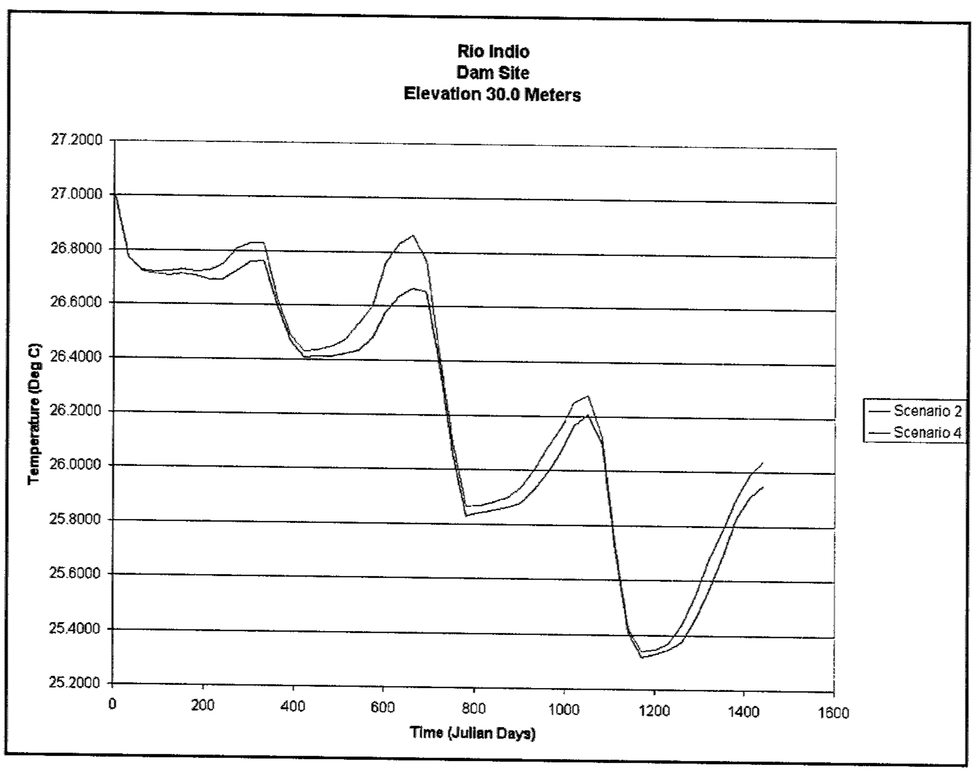

Figure 7-39. Temperature, elevation 30.0, at dam site

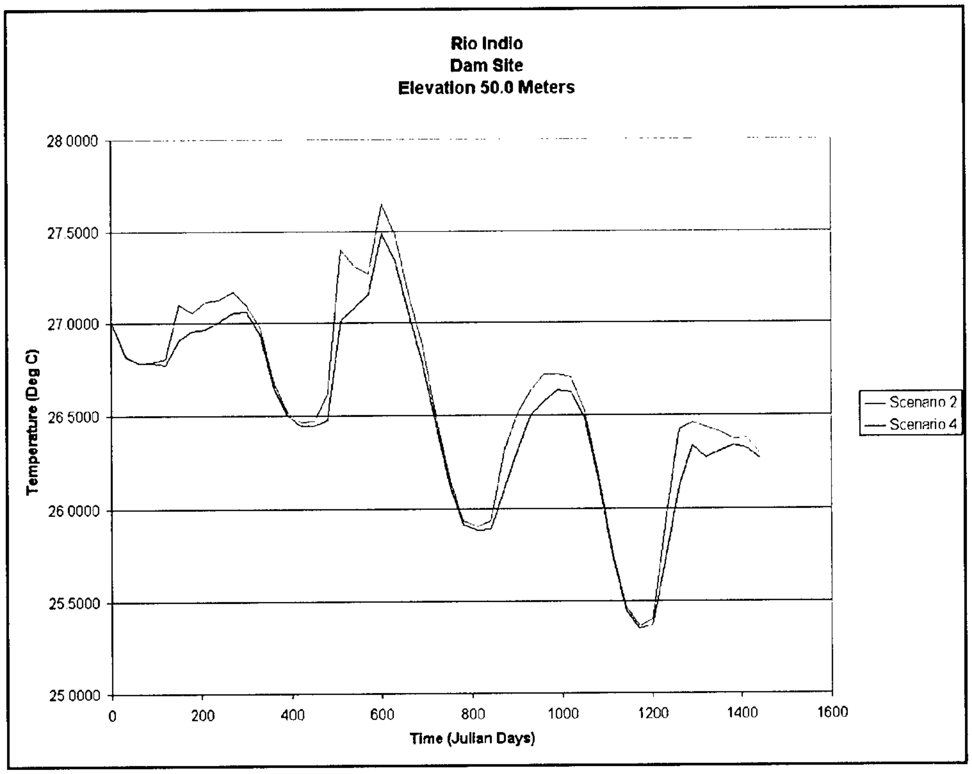

Figure 7-40. Temperature, elevation 50.0, at dam site

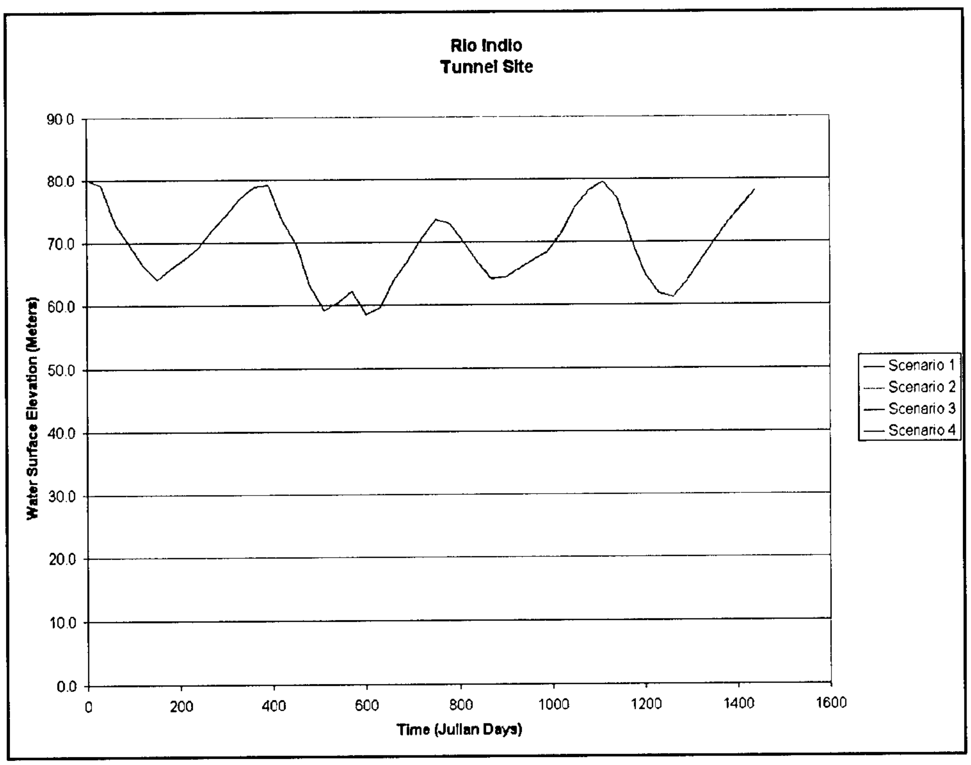

Figure 7-41. WSEL at tunnel site

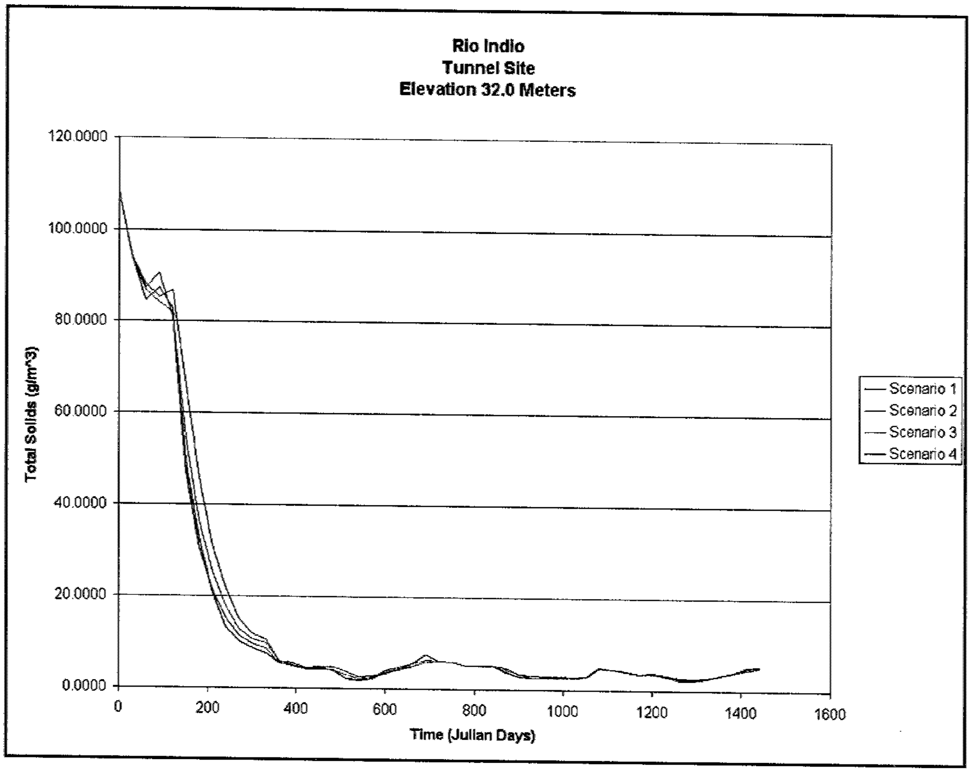

Figure 7-42. Total Solids, elevation 32.0, at tunnel site

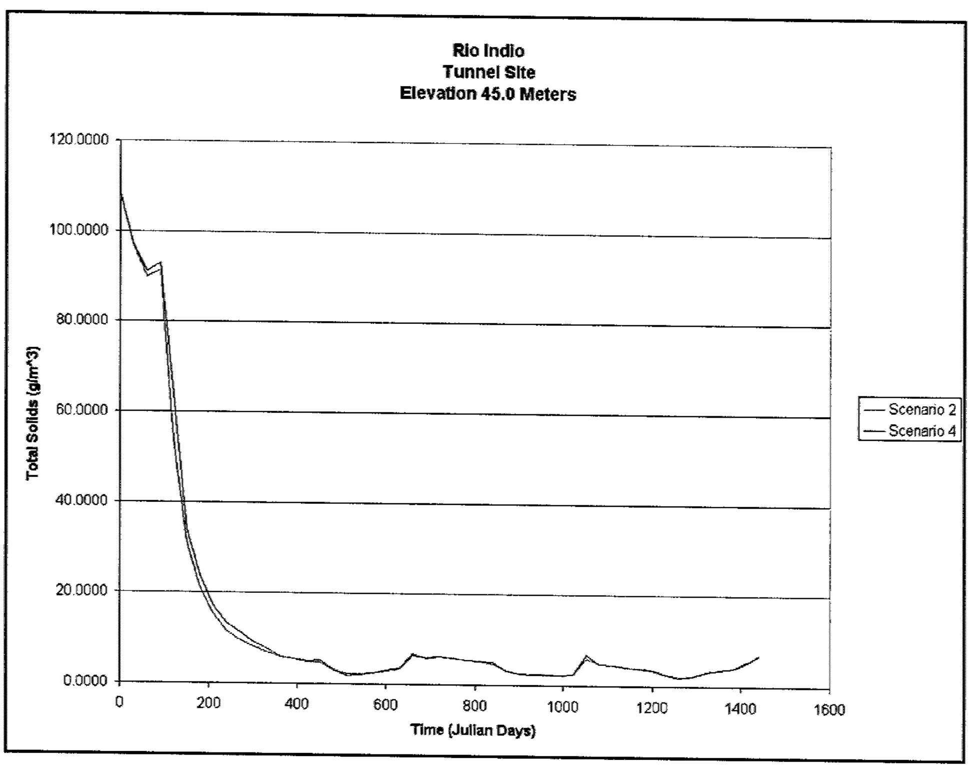

Figure 7-43. Total Solids, elevation 45.0, at tunnel site

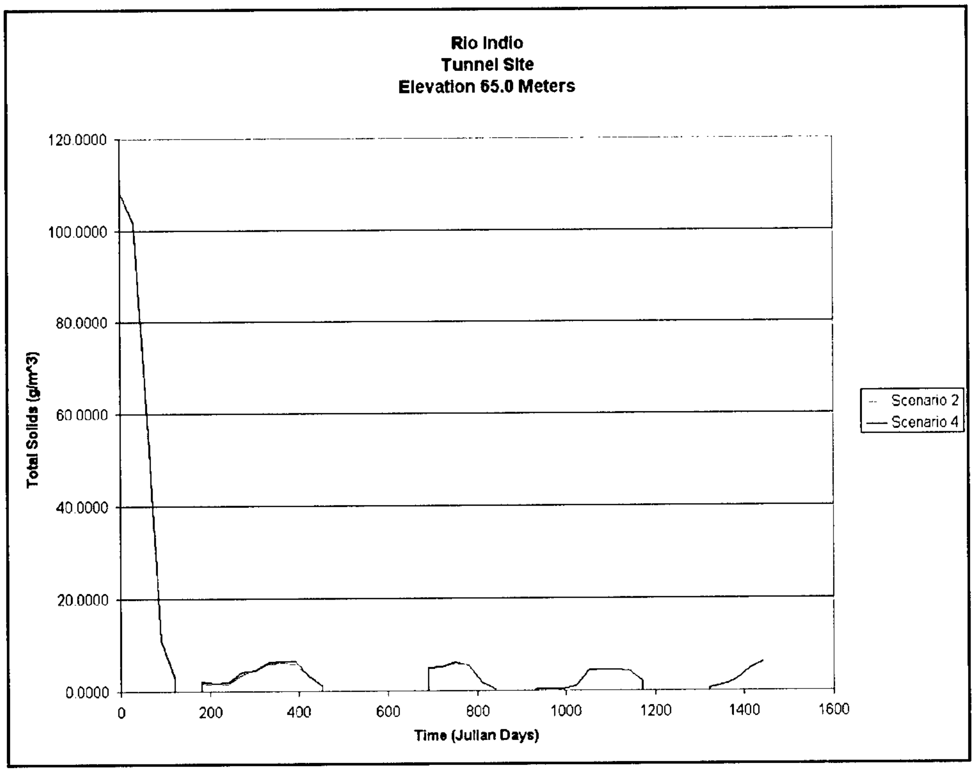

Figure 7-44. Total Solids, elevation 65.0, at tunnel site

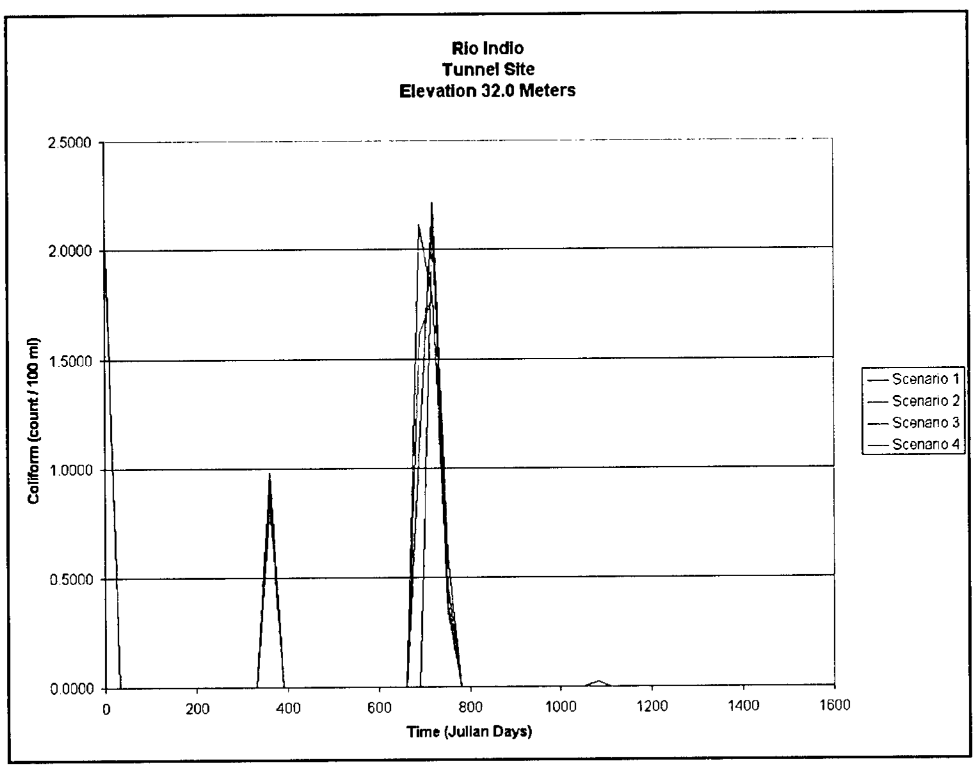

Figure 7-45. Coliform, elevation 32.0, at tunnel site

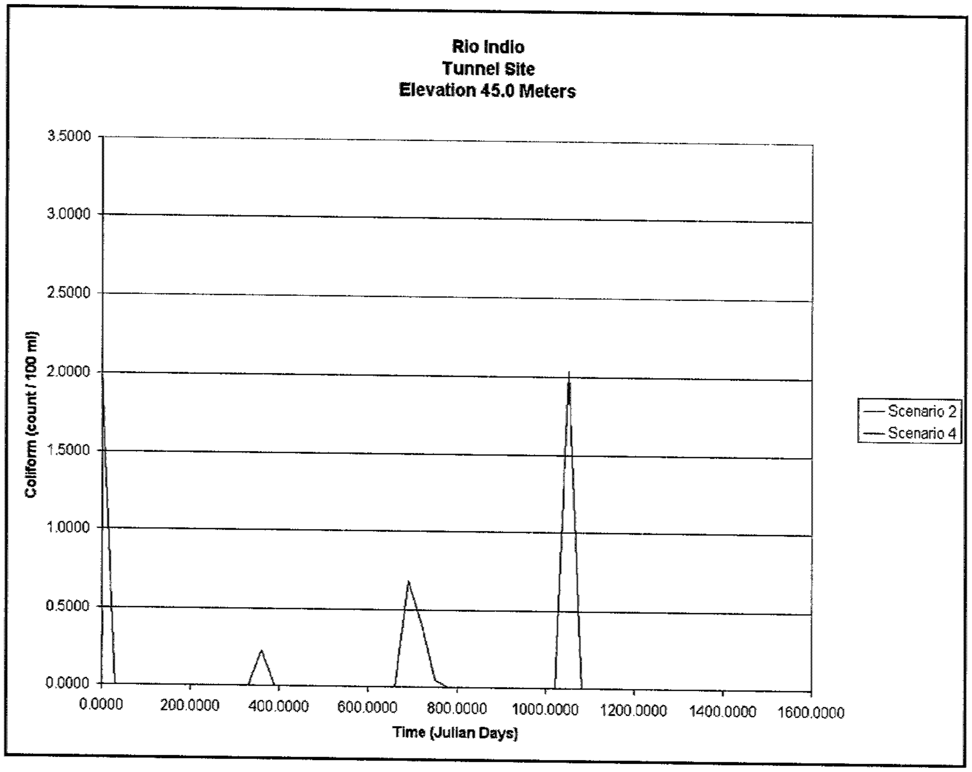

Figure 7-46. Coliform, elevation 45.0, at tunnel site

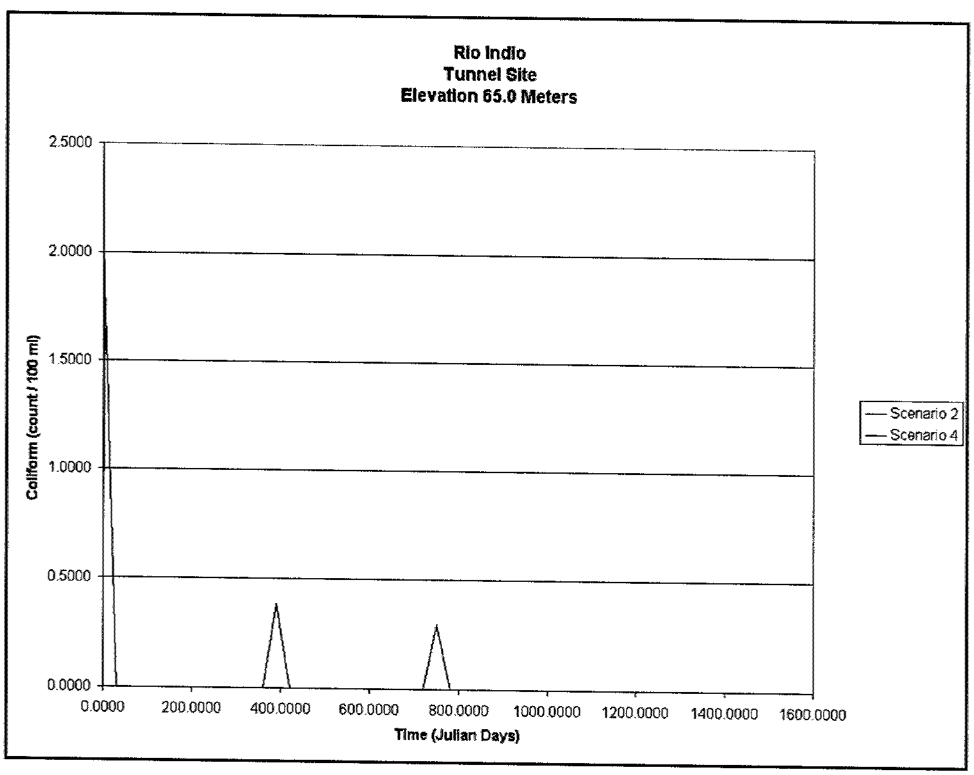

Figure 7-47. Coliform, elevation 65.0, at tunnel site

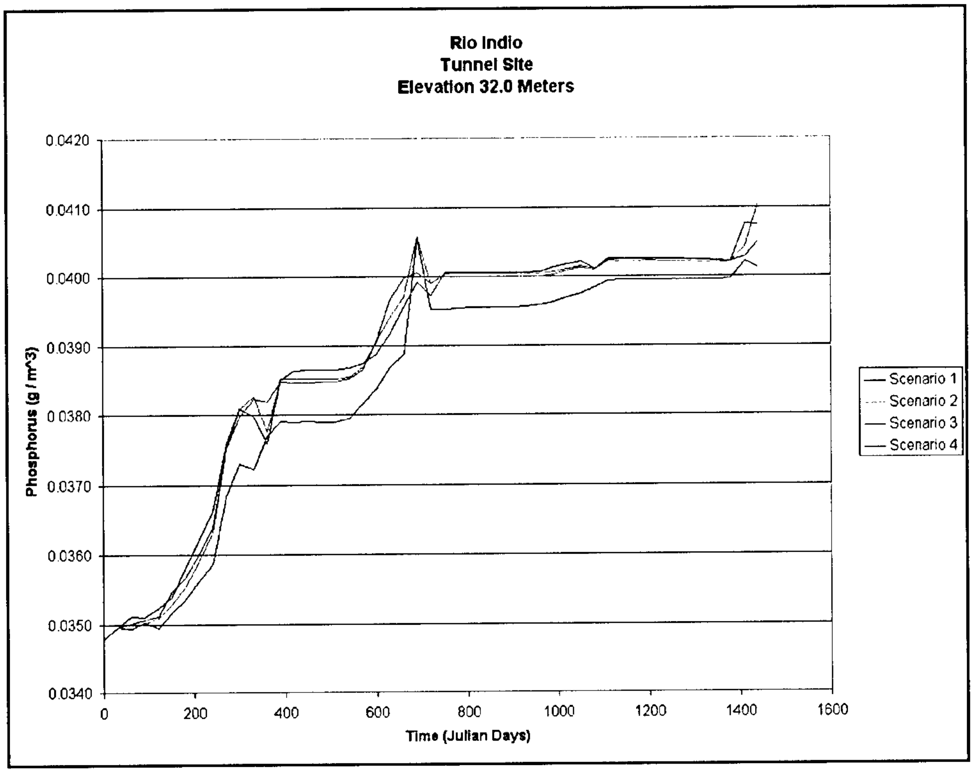

Figure 7-48. Phosphorus, elevation 32.0, at tunnel site

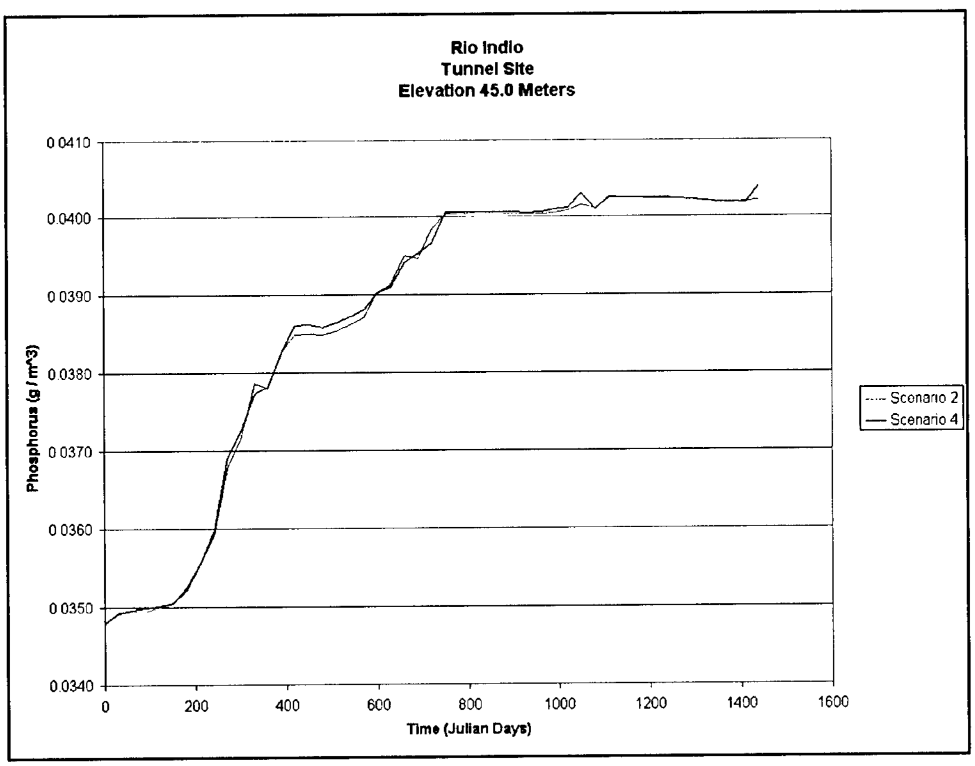

Figure 7-49. Phosphorus, elevation 45.0, at tunnel site

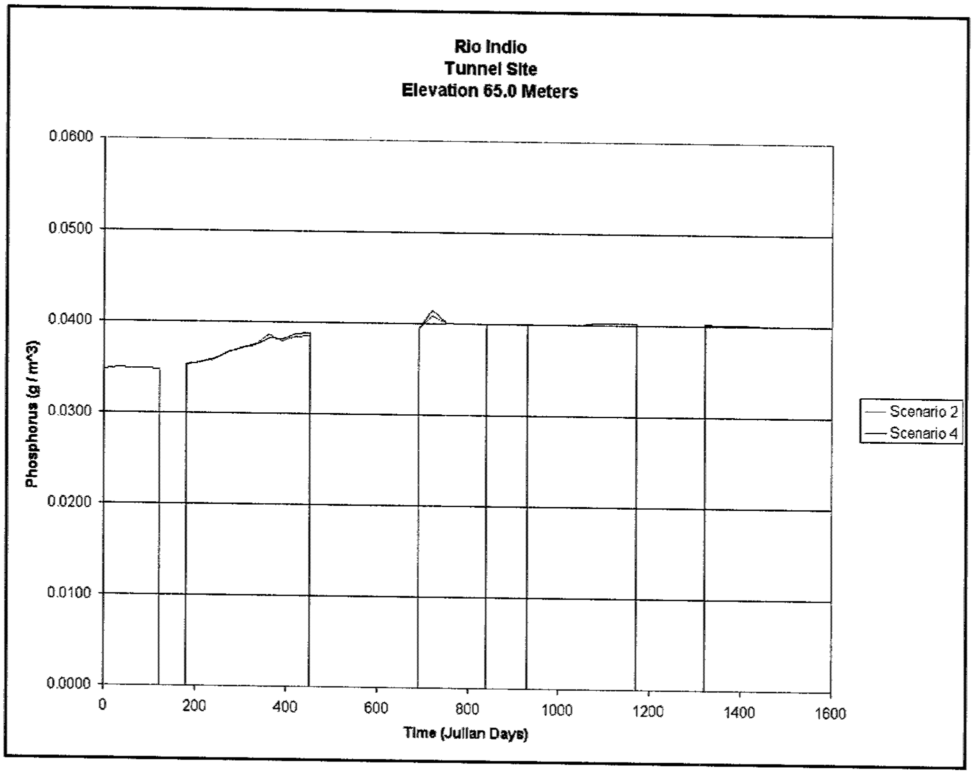

Figure 7-50. Phosphorus, elevation 65.0, at tunnel site

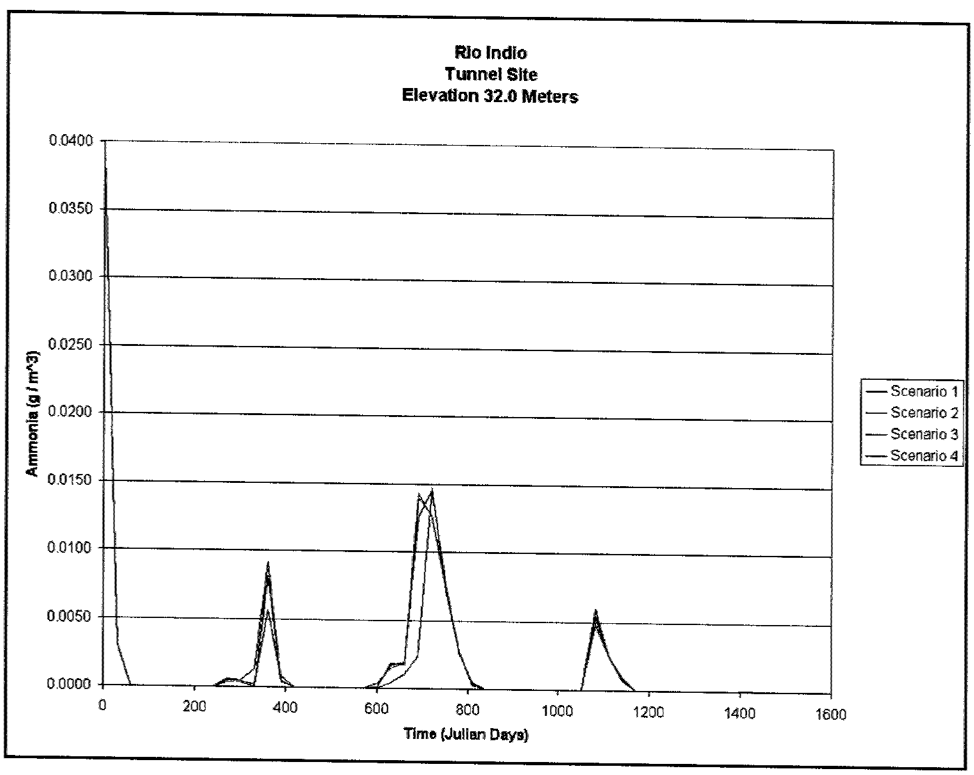

Figure 7-51. Ammonia, elevation 32.0, at tunnel site

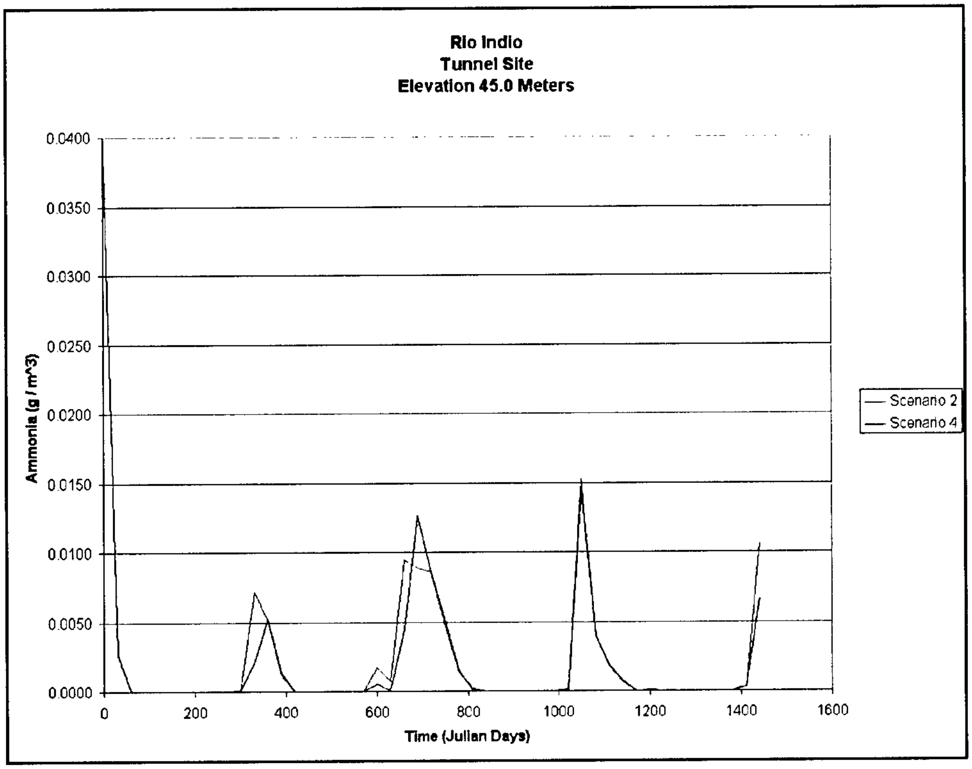

Figure 7-52. Ammonia, elevation 45.0, at tunnel site

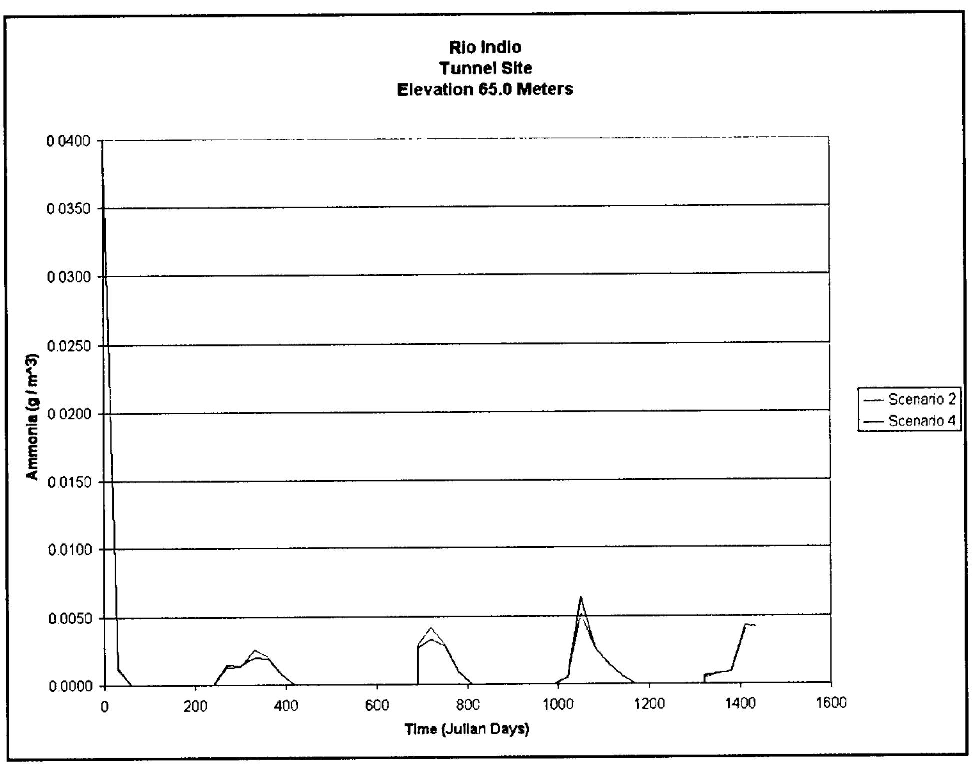

Figure 7-53. Ammonia, elevation 65.0, at tunnel site

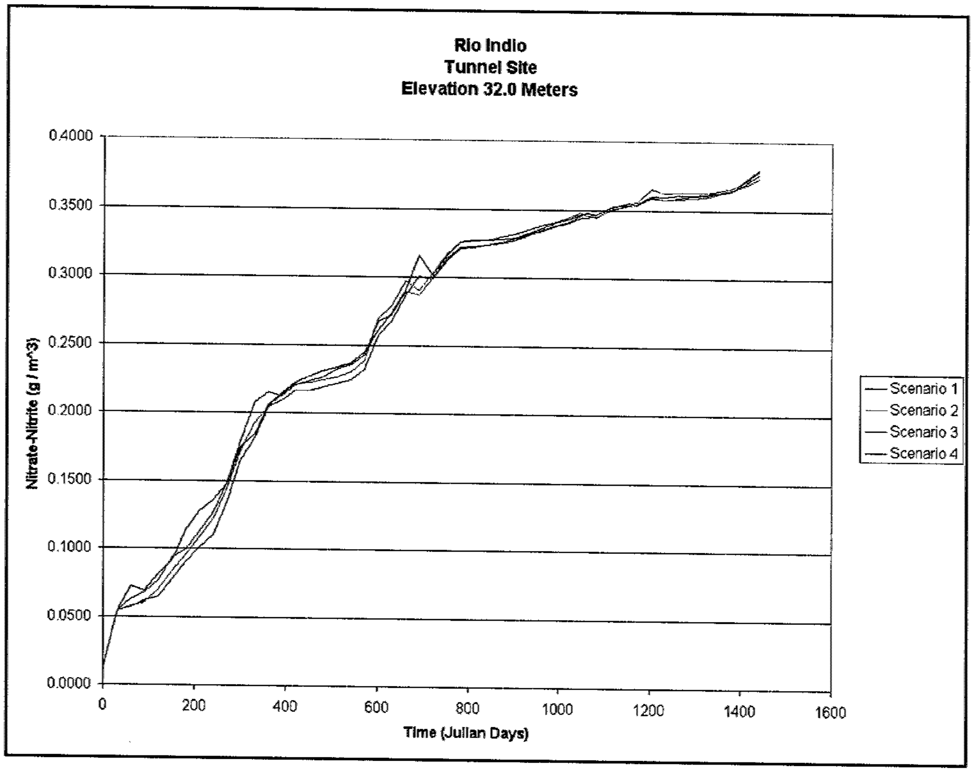

Figure 7-54. Nitrate-nitrite, elevation 32.0, at tunnel site

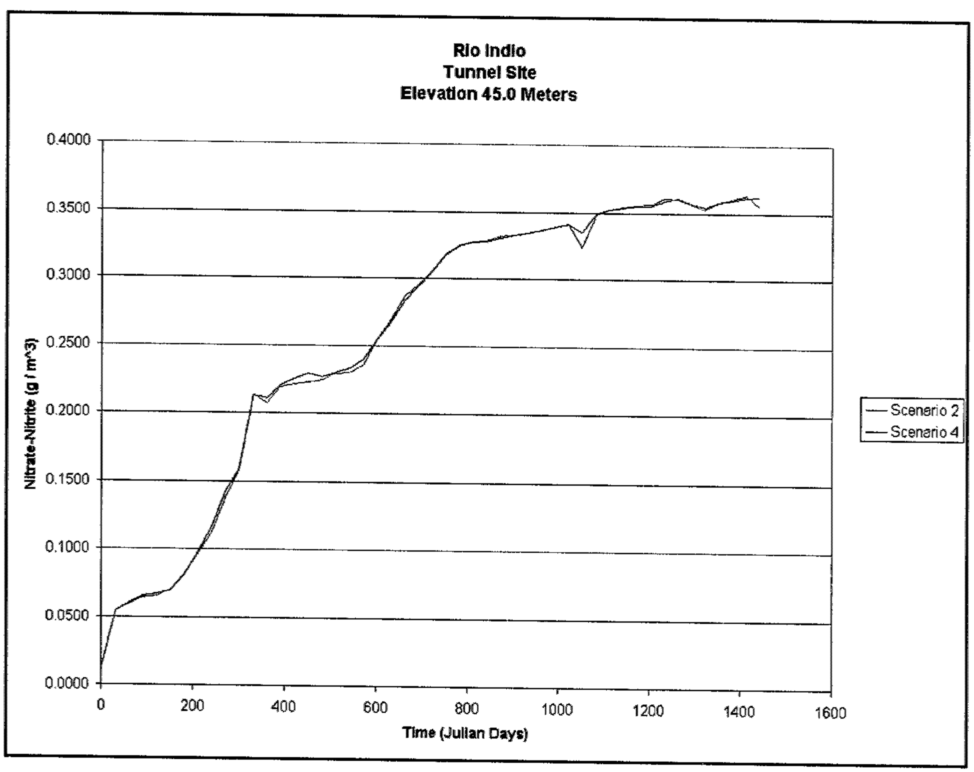

Figure 7-55. Nitrate-nitrite, elevation 45.0, at tunnel site

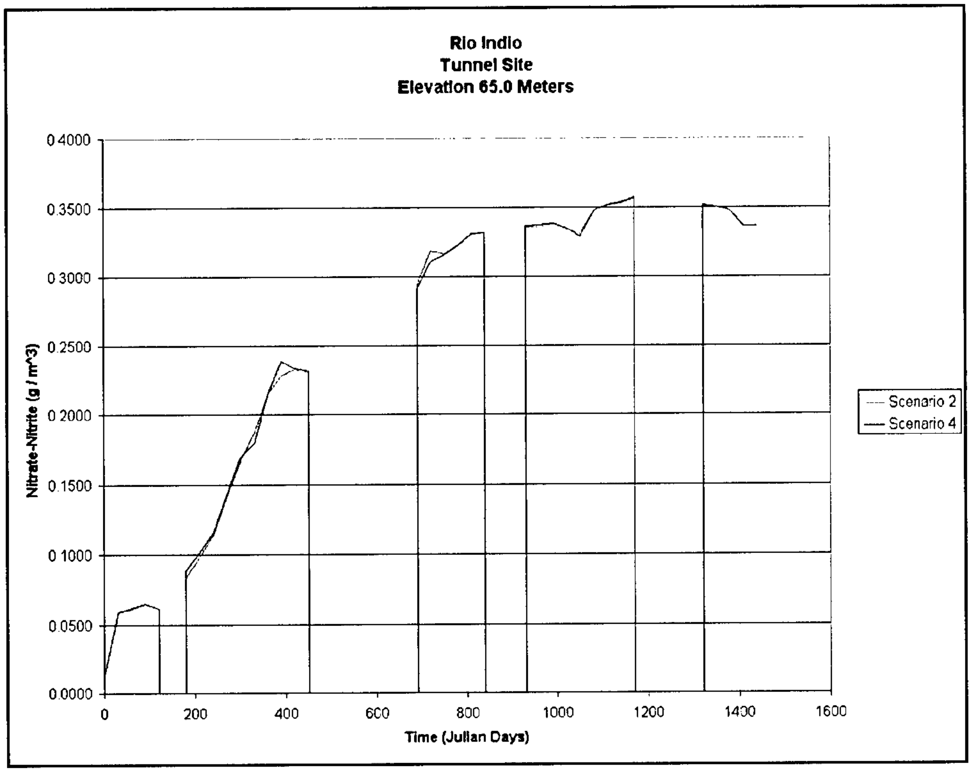

Figure 7-56. Nitrate-nitrite, elevation 65.0, at tunnel site

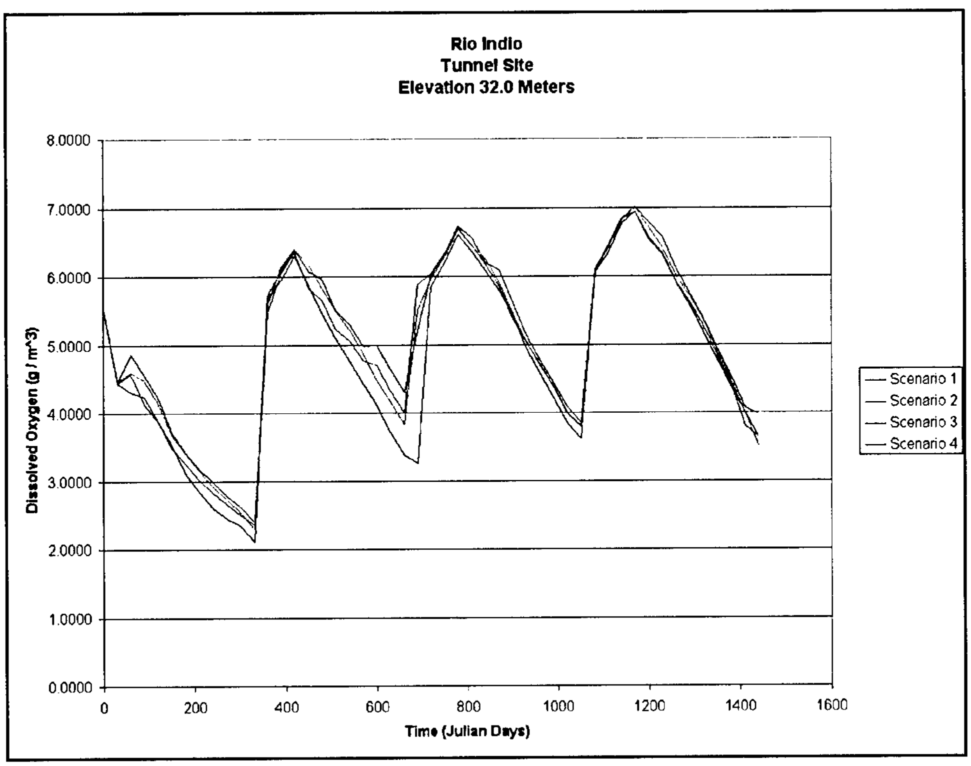

Figure 7-57. Dissolved oxygen, elevation 32.0, at tunnel site

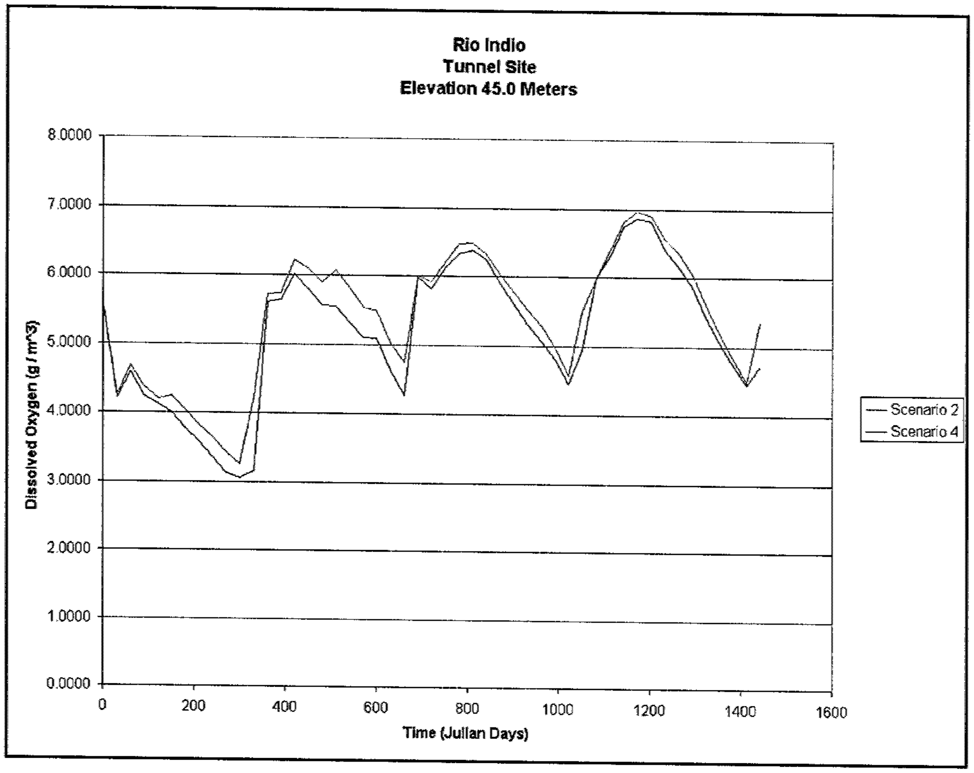

Figure 7-58. Dissolved oxygen, elevation 45.0, at tunnel site

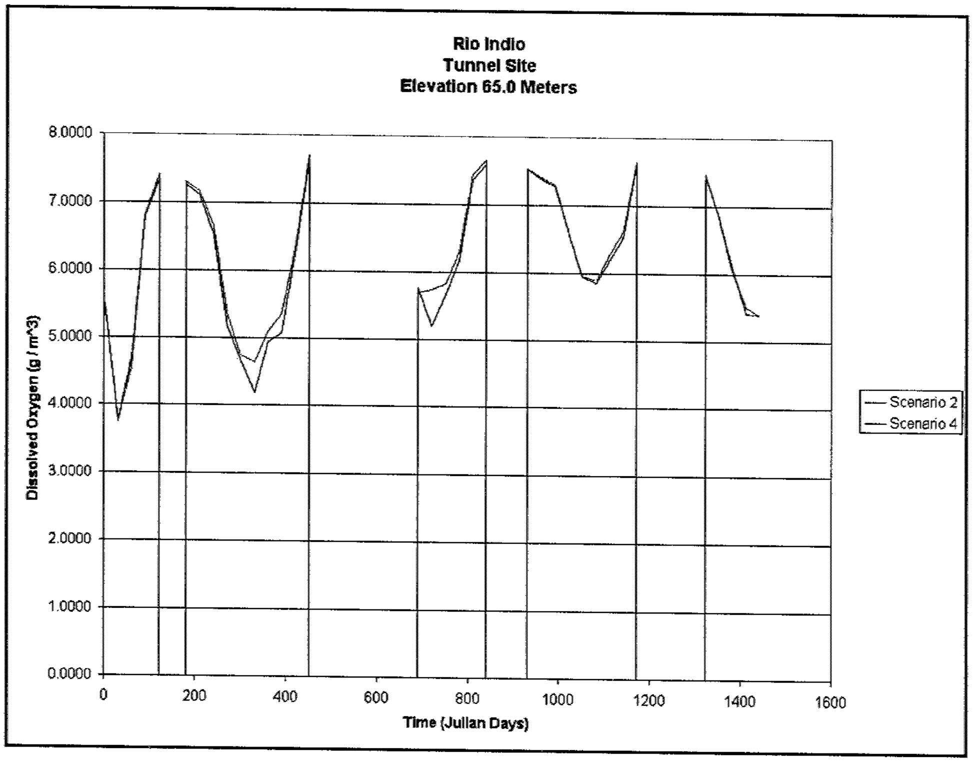

Figure 7-59. Dissolved oxygen, elevation 65.0, at tunnel site

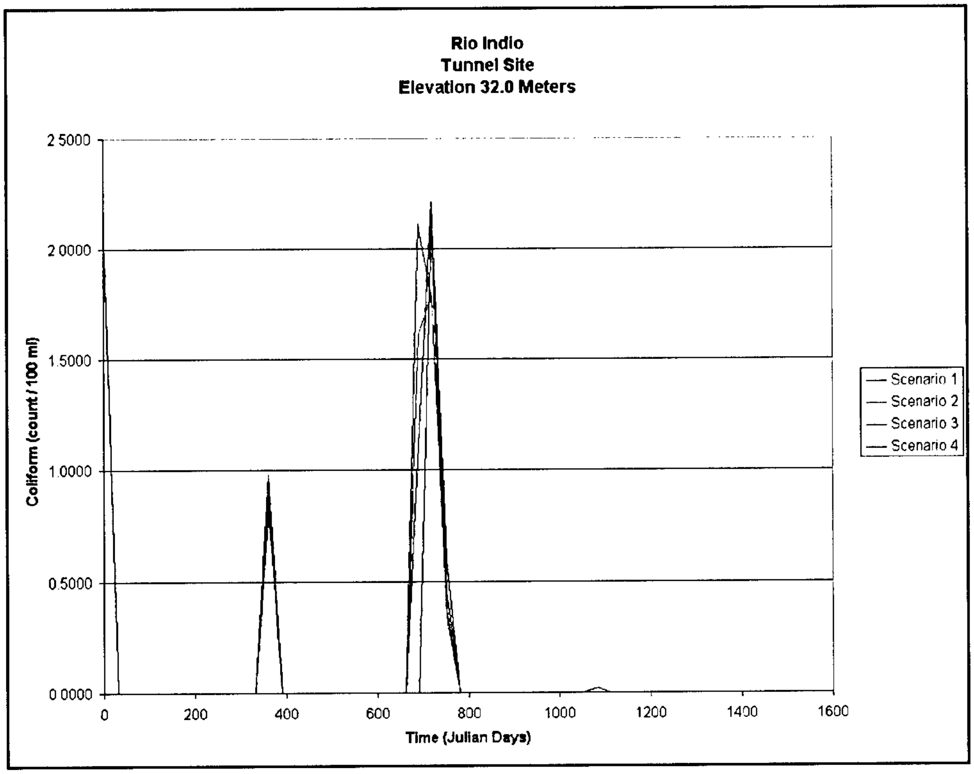

Figure 7-60. CBOD, elevation 32.0, at tunnel site

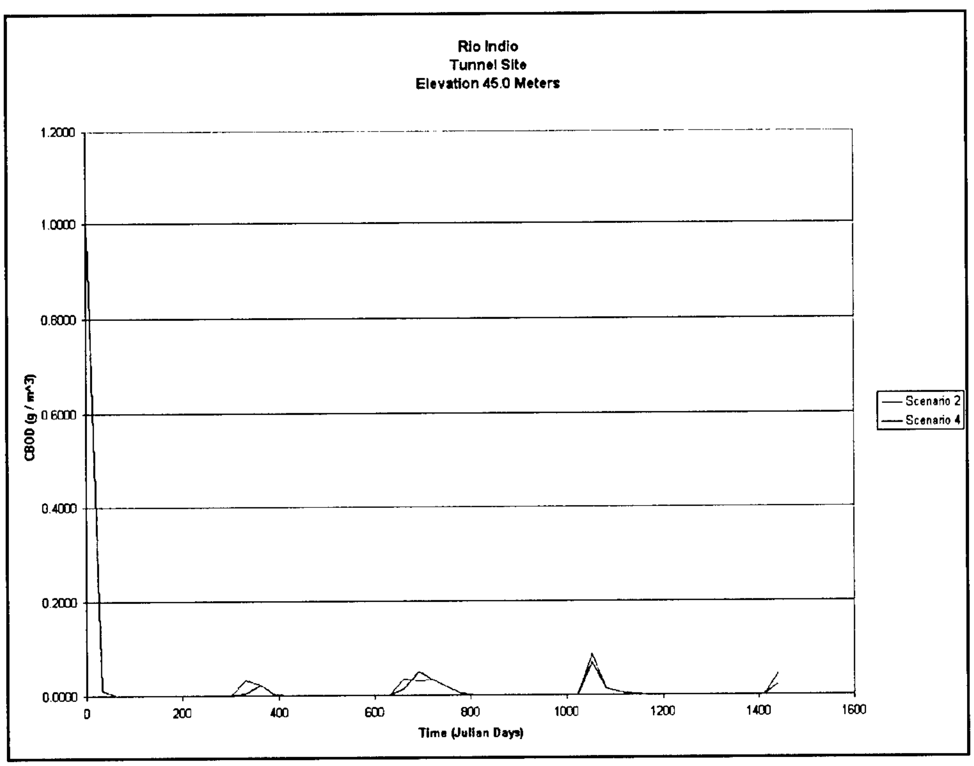

Figure 7-61. CBOD, elevation 45.0, at tunnel site

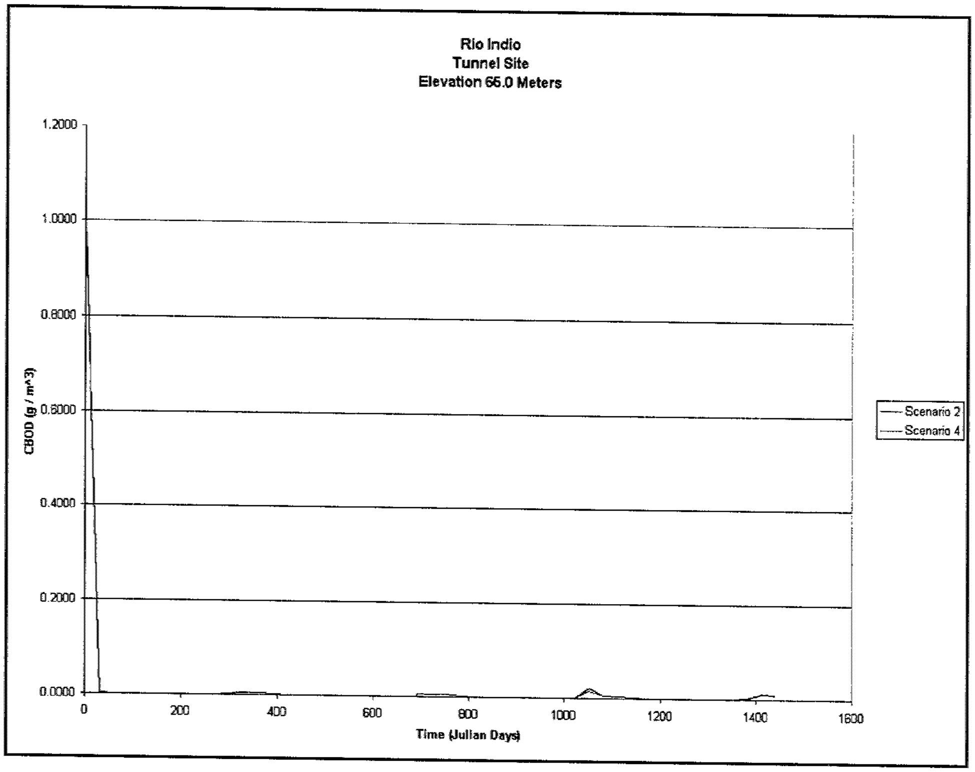

Figure 7-62. CBOD, elevation 65.0, at tunnel site

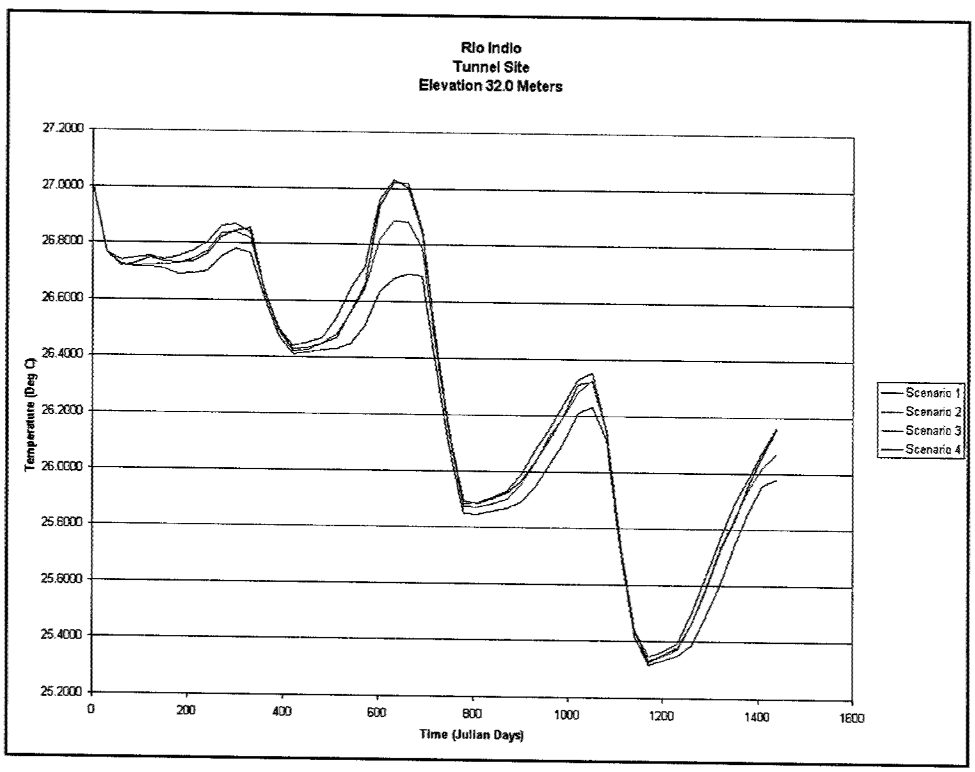

Figure 7-63. Temperature, elevation 32.0, at tunnel site

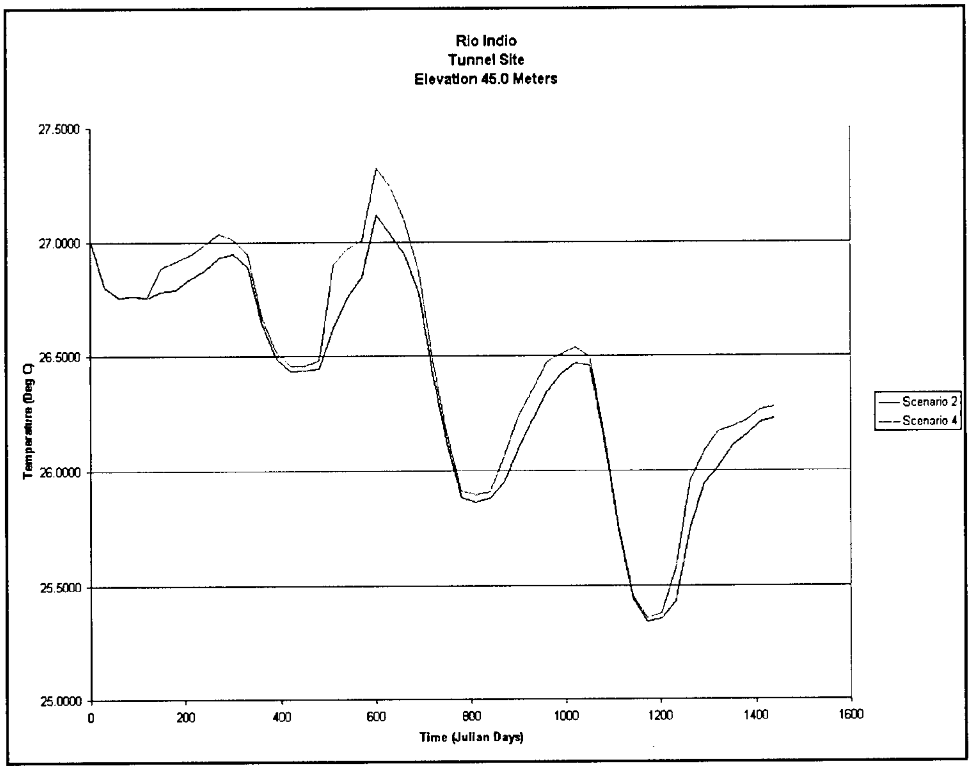

Figure 7-64. Temperature, elevation 45.0, at tunnel site

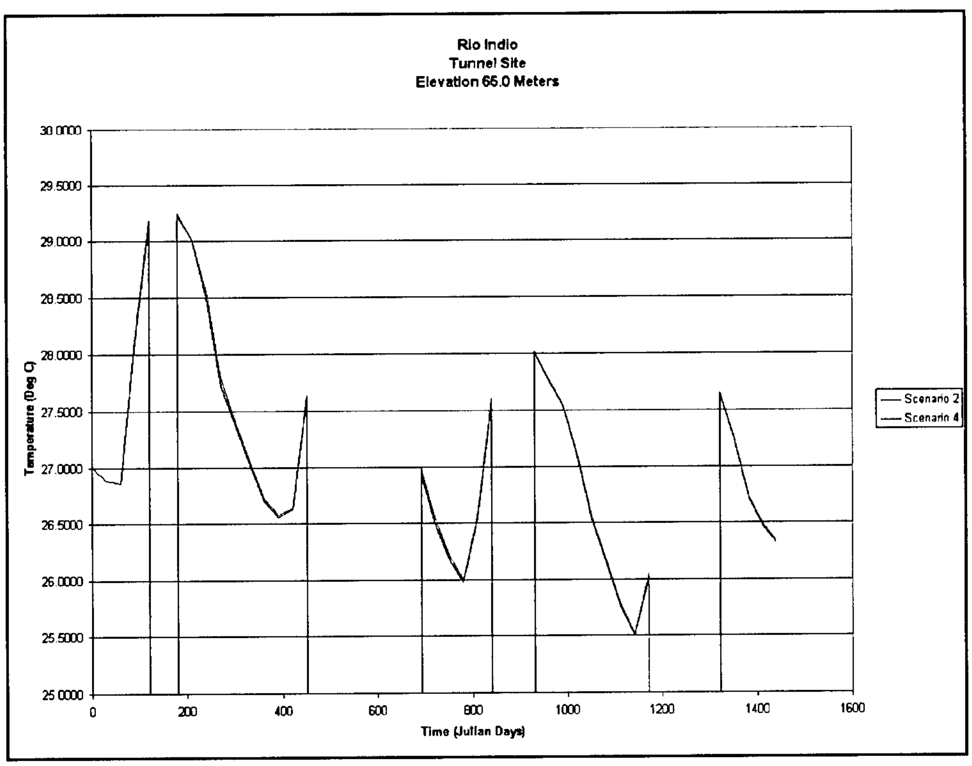

Figure 7-65. Temperature, elevation 65.0, at tunnel site

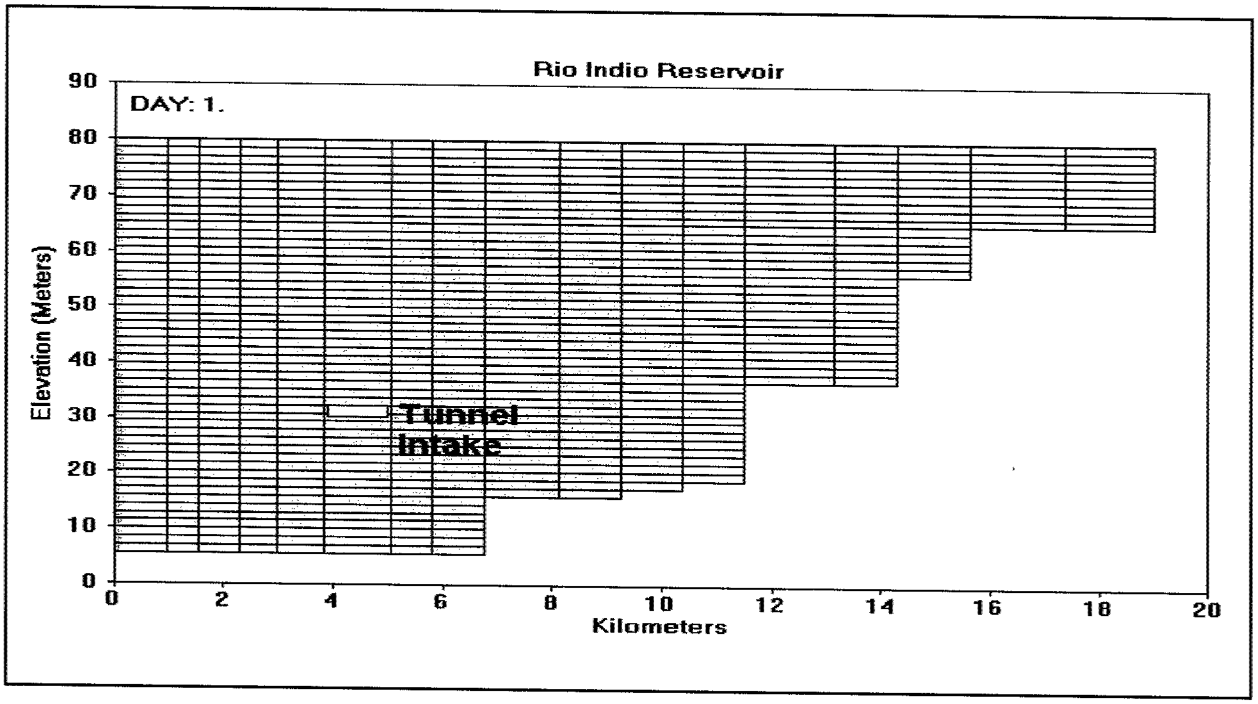

Figure 7-66. Rio Indio Reservoir main branch segmentation with inter-basin tunnel intake location shown

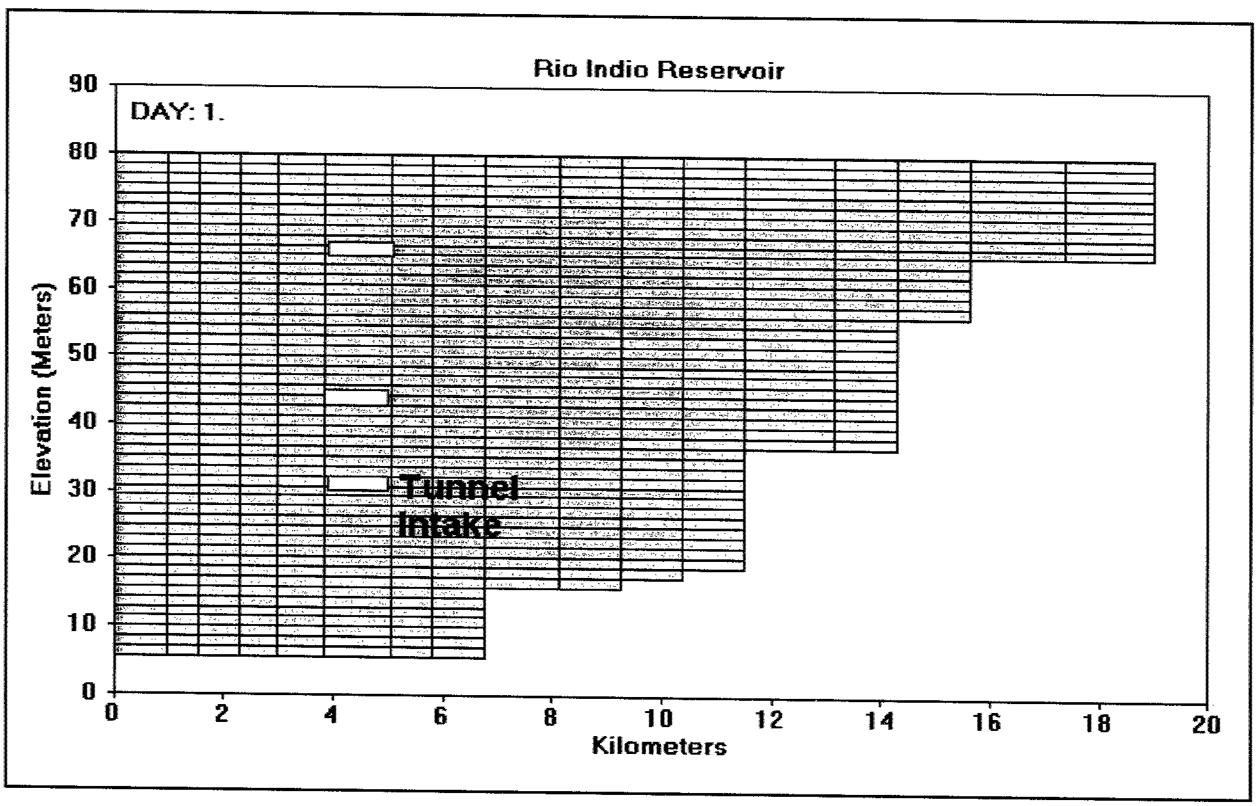

Figure 7-67. Rio Indio Reservoir main branch segmentation with inter-basin tunnel multiple-intake location shown

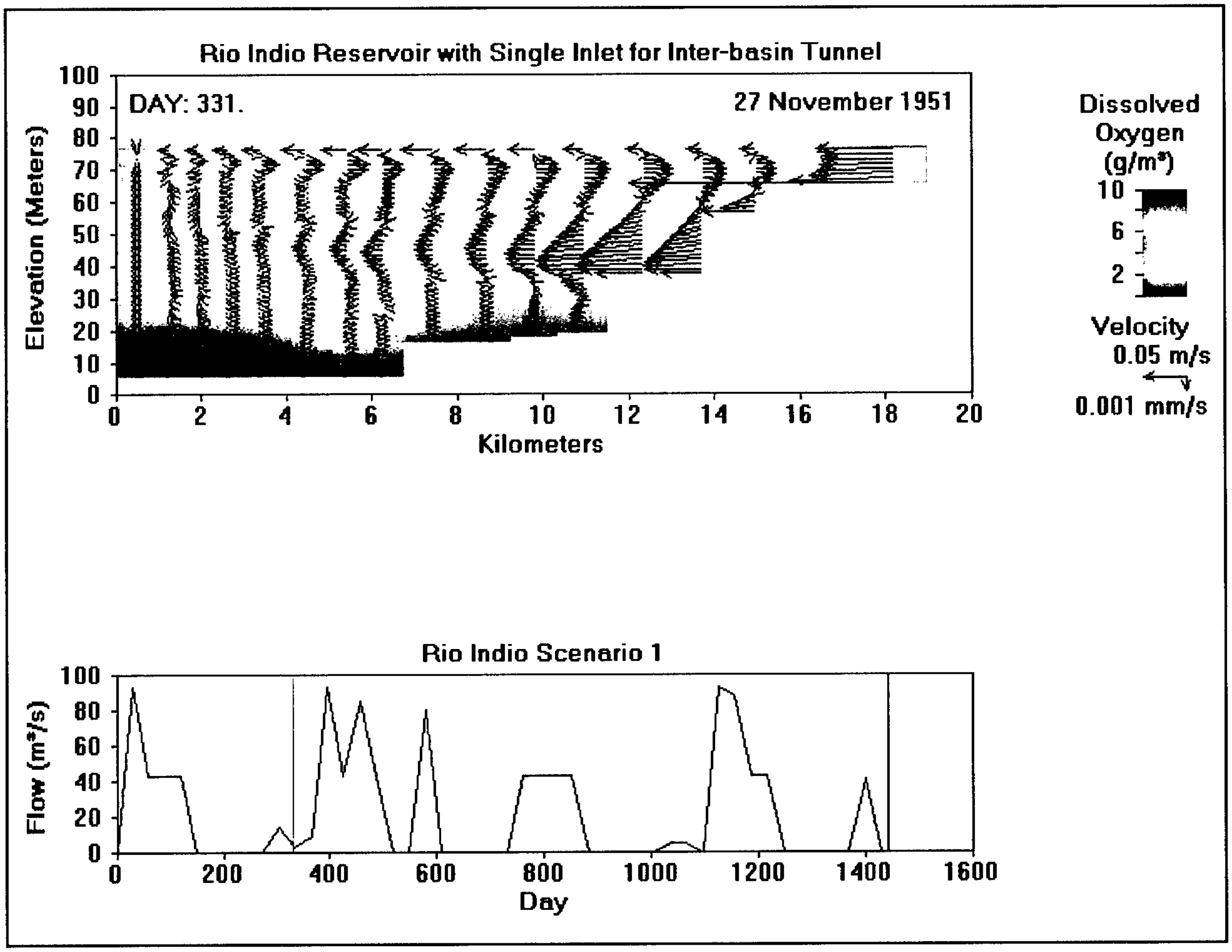

Figure 7-68. Rio Indio Reservoir main branch dissolved oxygen day 331 of simulation, beginning of inter-basin transfer with single tunnel inlet

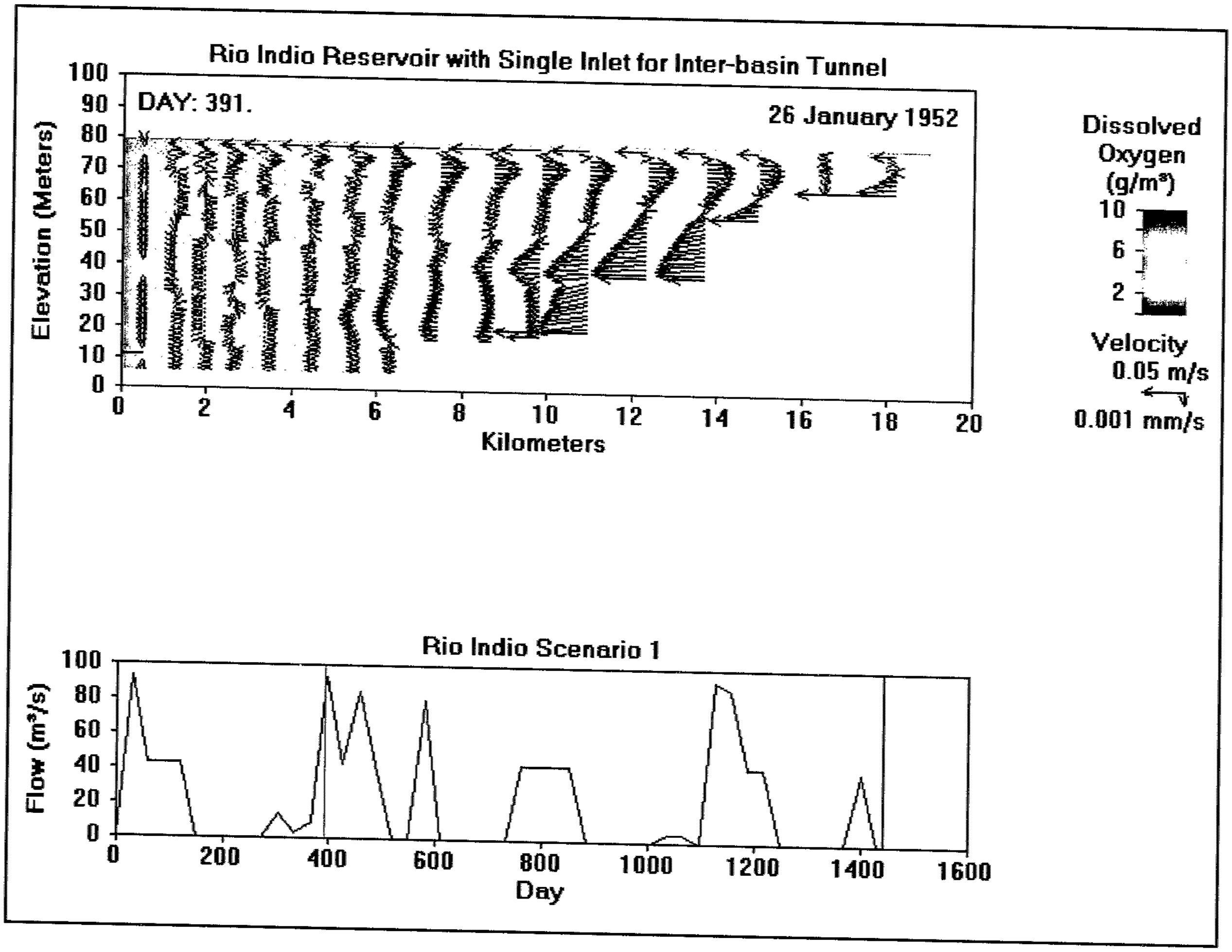

Figure 7-69. Rio Indio Reservoir main branch dissolved oxygen day 391 of simulation, peak flow for inter-basin transfer with single tunnel inlet

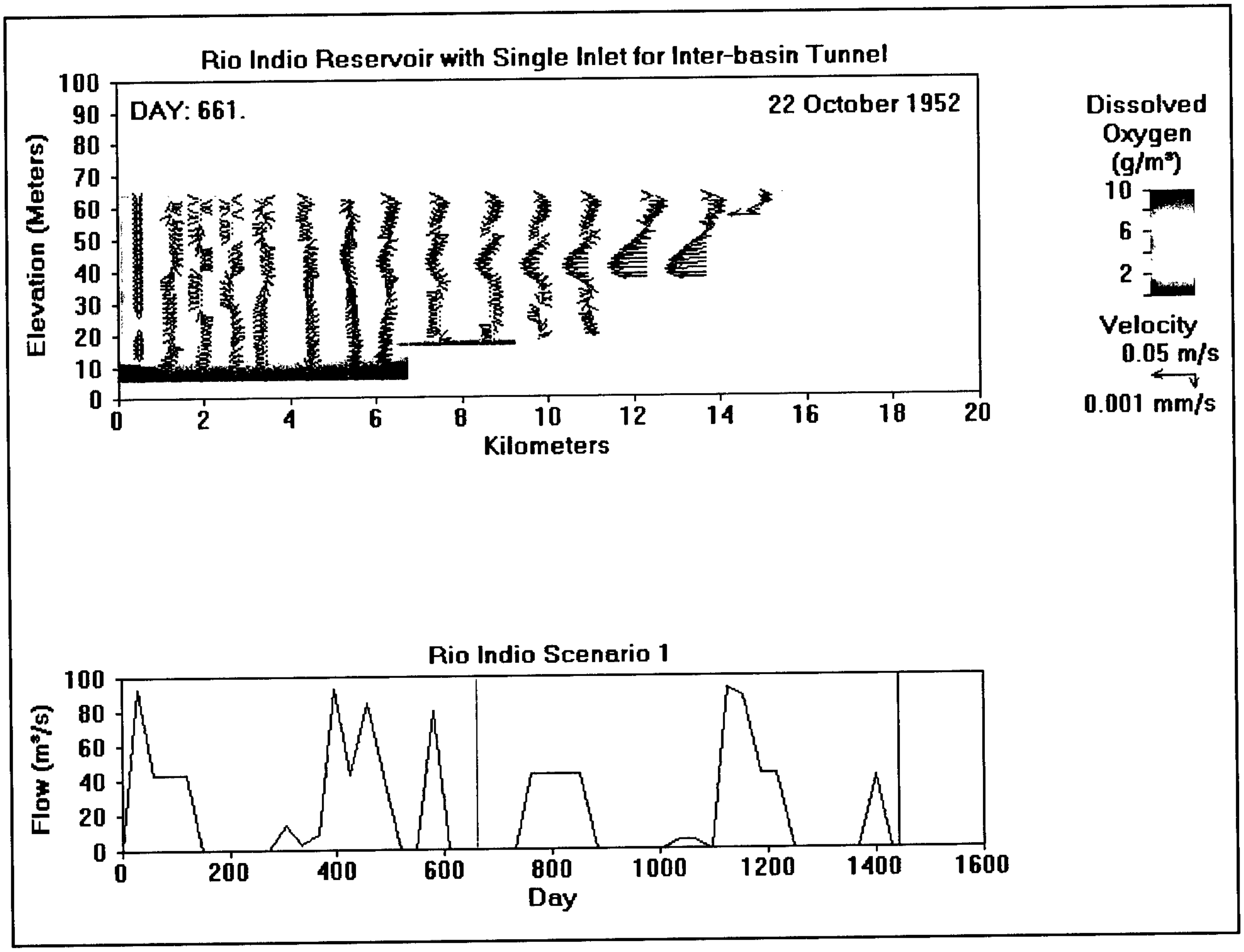

Figure 7-70. Rio Indio Reservoir main branch dissolved oxygen day 661 of simulation, no inter-basin transfer with single tunnel inlet

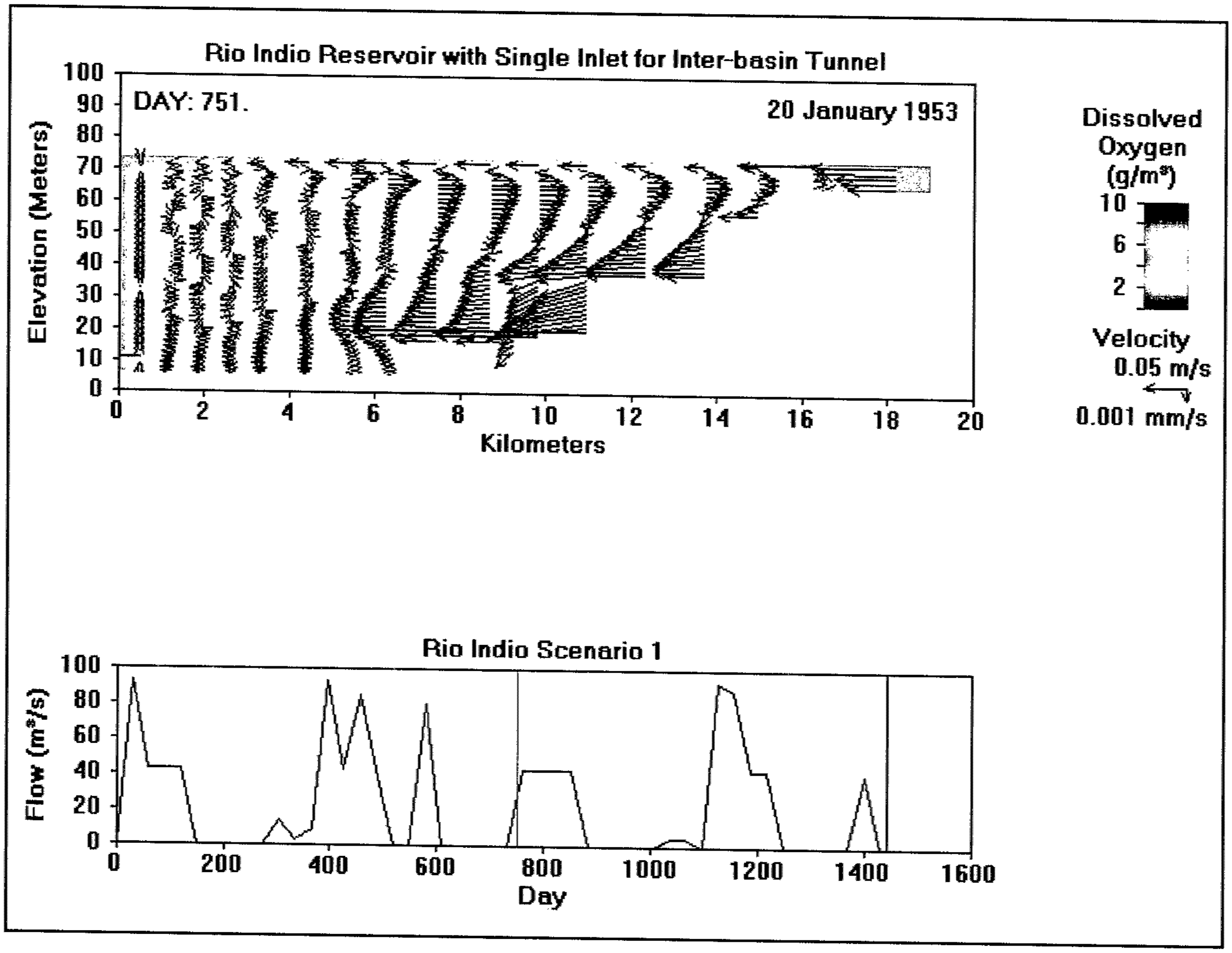

Figure 7-71. Rio Indio Reservoir main branch dissolved oxygen day 751 of simulation, inter-basin transfer with single tunnel inlet

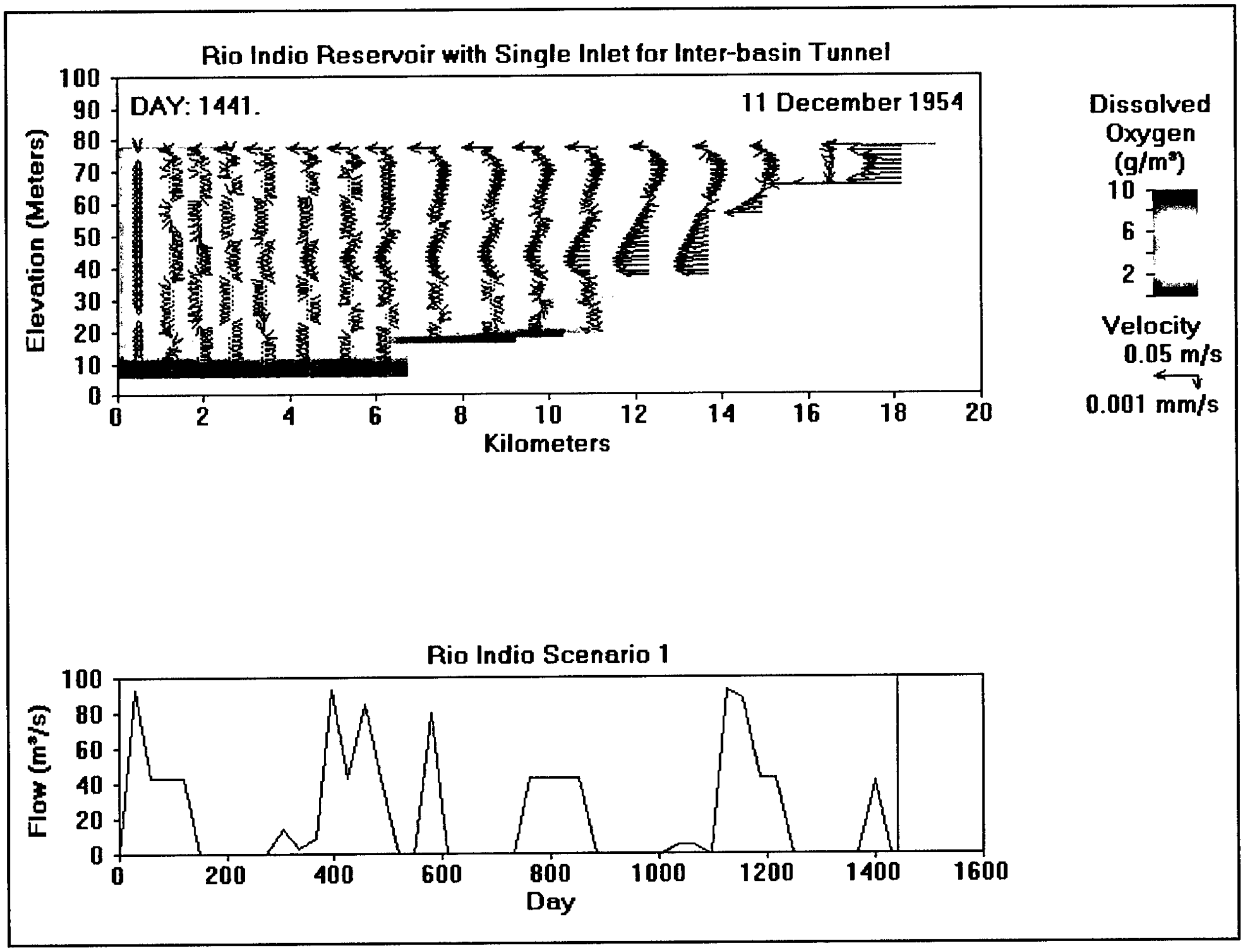

Figure 7-72. Rio Indio Reservoir main branch dissolved oxygen day 1441 of simulation, no inter-basin transfer with single tunnel inlet

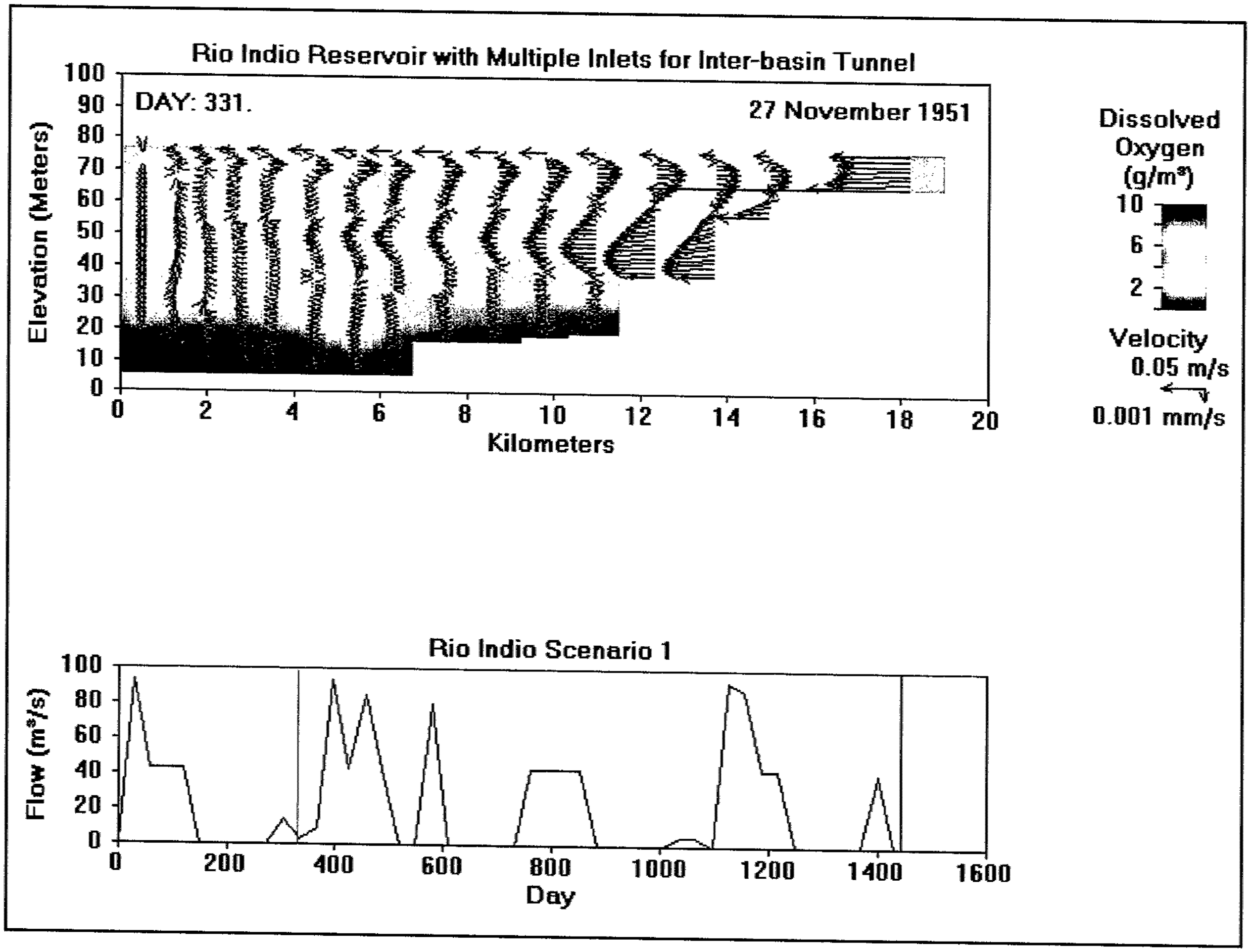

Figure 7-73. Rio Indio Reservoir main branch dissolved oxygen day 331 of simulation, beginning of inter-basin transfer with multiple tunnel inlets

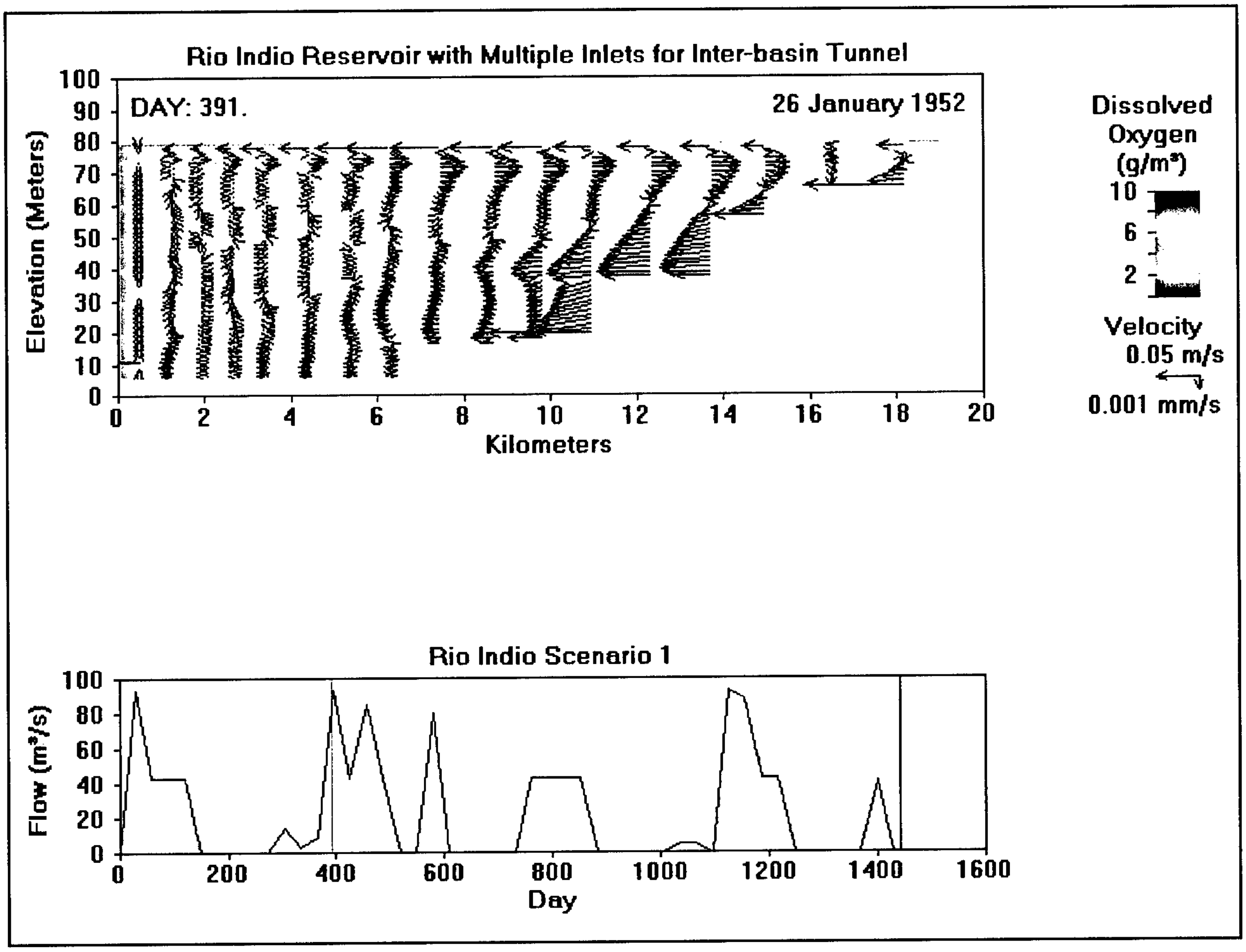

Figure 7-74. Rio Indio Reservoir main branch dissolved oxygen day 391 of simulation, peak flow for inter-basin transfer with multiple tunnel inlets

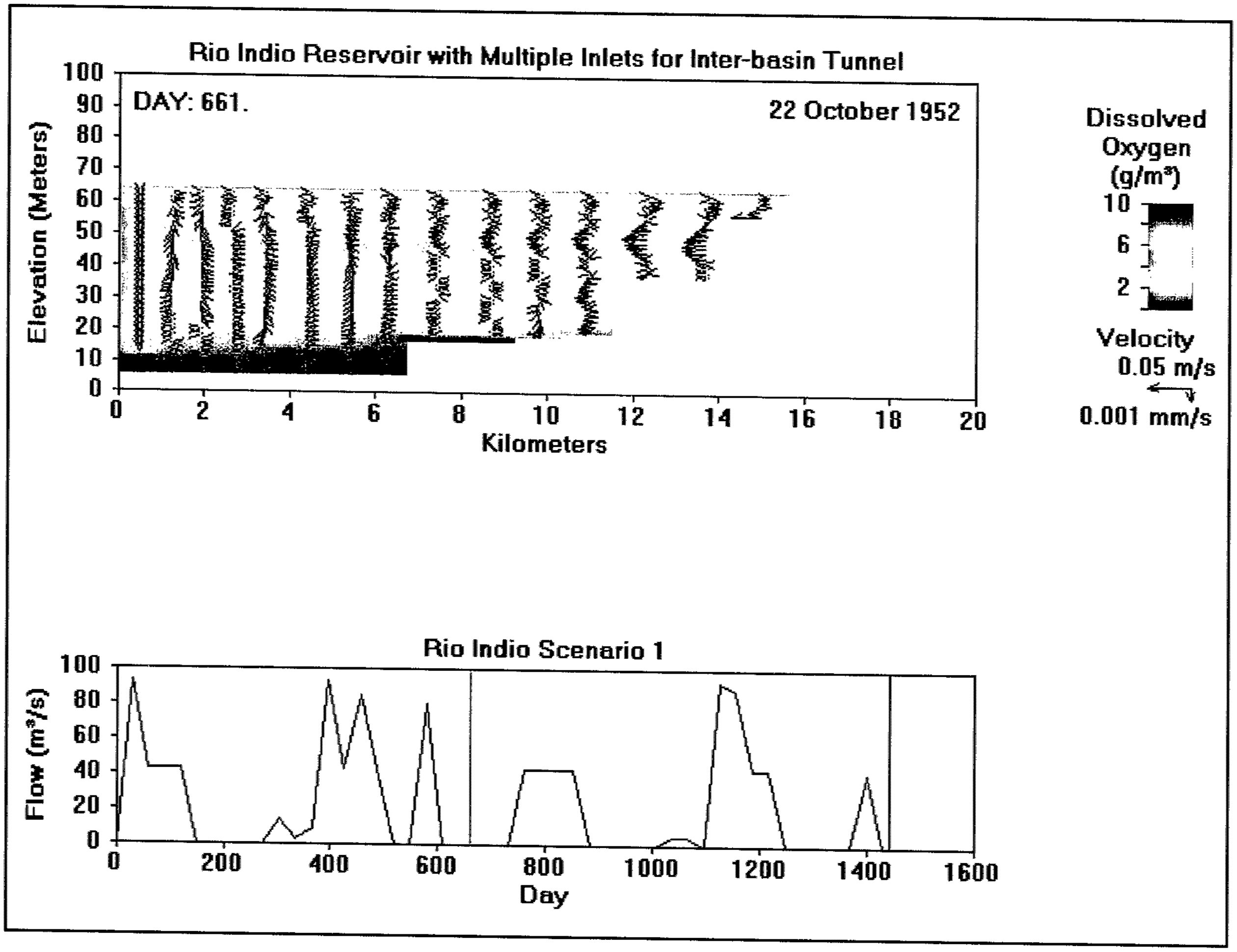

Figure 7-75. Indio Reservoir main branch dissolved oxygen day 661 of simulation, no inter-basin transfer with multiple tunnel inlets

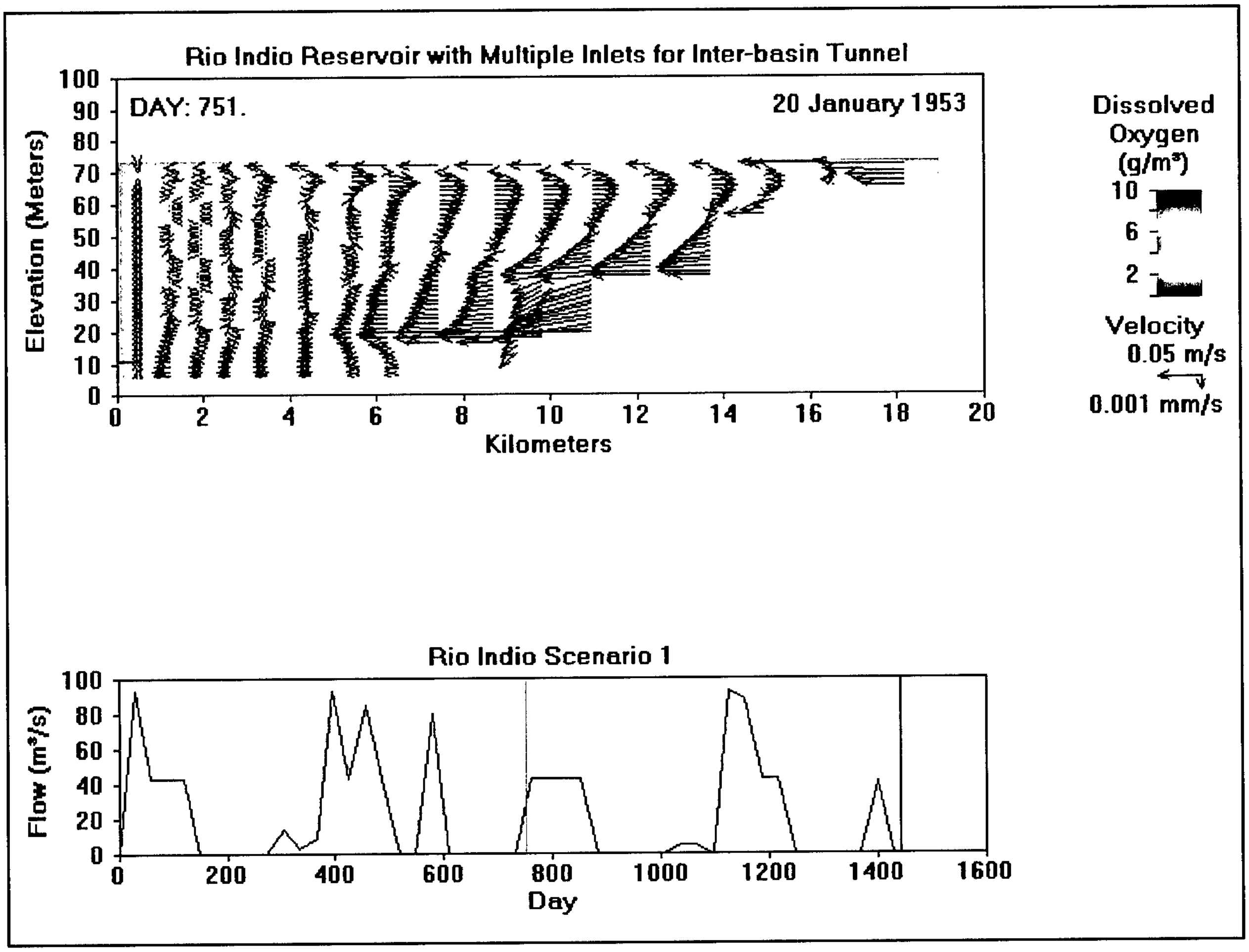

Figure 7-76. Rio Indio Reservoir main branch dissolved oxygen day 751 of simulation, inter-basin transfer with multiple tunnel inlets

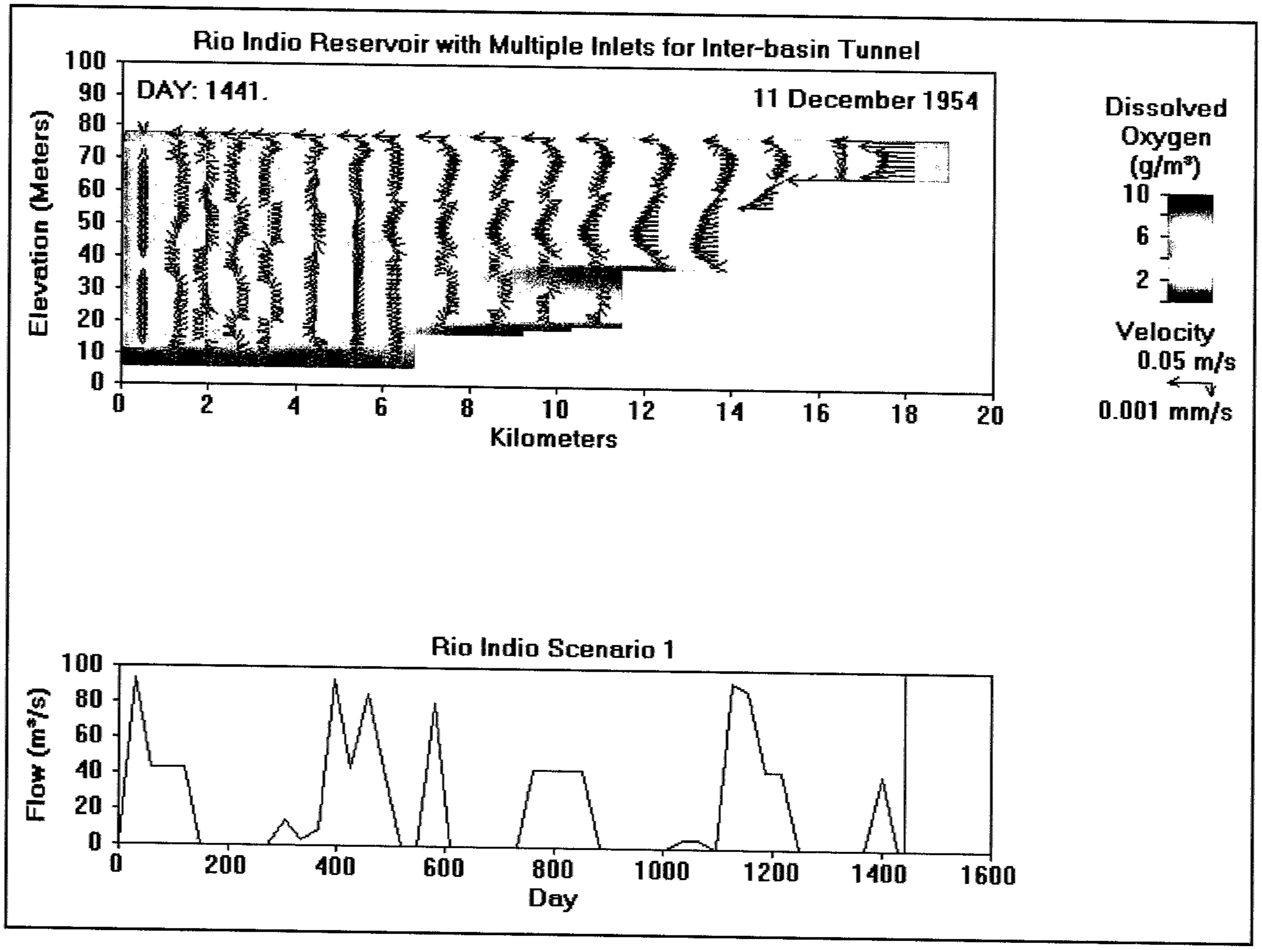

Figure 7-77. Rio Indio Reservoir main branch dissolved oxygen day 1441 of simulation, no inter-basin transfer with multiple tunnel inlets

Gatun Lake

Model setup

Two four year (1951-1954) simulations of Gatun Lake were run in which inter-basin transfer flows from the Rio Indio tunnel were discharged into the segment corresponding to the tunnel discharge site location. Both scenarios used the same inflows and outflows, the difference between the two simulations being the water quality conditions of the Rio Indio inter-basin transfer water. In one case the water was withdrawn from Rio Indio through a single bottom outlet at 32m el. In the second case a multi-level intake was simulated with inter-basin transfer flow being equally divided between the three ports of the multi-level intake. As with the Rio Indio simulations, HEC-5 output information was used to set up the inflows and water demands for Gatun Lake. The computed evaporation from the HEC-5 results was subtracted from the local inflow and Lake Madden discharge provided by HEC-5 in order to generate net inflows. The local inflows were proportioned to the major tributaries as is shown in Table 7-4. This distribution was developed based upon the average flows for these three tributaries indicated in Table 7-4.

Table 7-4 Flow Apportionment for Lake Gatun Scenario	
Tributary	Percent of Net Inflow (Local Inflow – Evaporation)
Rio Gatun	29.4%
Rio Ciri Grande	29.9%
Rio Trinidad	23.2%
Rio Chilibre	17.5%

Outflows from Gatun Lake for these scenarios are divided into two categories: water demand for navigation and water demand for M&I consumption. The HEC-5 simulation that served as the basis for these scenarios was one in which all possible water in Gatun Lake was being used these two purposes. HEC-5 input information and output were used to compute the total outflow and its distribution between navigation and M&I demands. Demand output by HEC-5 was assigned to specific facilities based upon information gathered and used in the calibration of W2 for Gatun Lake, Table 7-5. Inflows and outflows for the Gatun Lake scenarios are shown in Figures 7-78–7-80.

Table 7-5 Water Demands Distribution for Gatun Lake Scenarios		
Demand	Facility	Flow % of Total Diversion
Navigation		95.8
	Gatun Locks (Atlantic)	48.4
	Pedro Miguel Locks (Pacific)	47.4
M&I		4.2
	Gamboa Water Intake	0.02
	Pariso water Intake	0.65
	Mt. Hope Water Intake	0.36
	Sabinitas Water Intake	0.132
	Escobal Water Intake	0.001

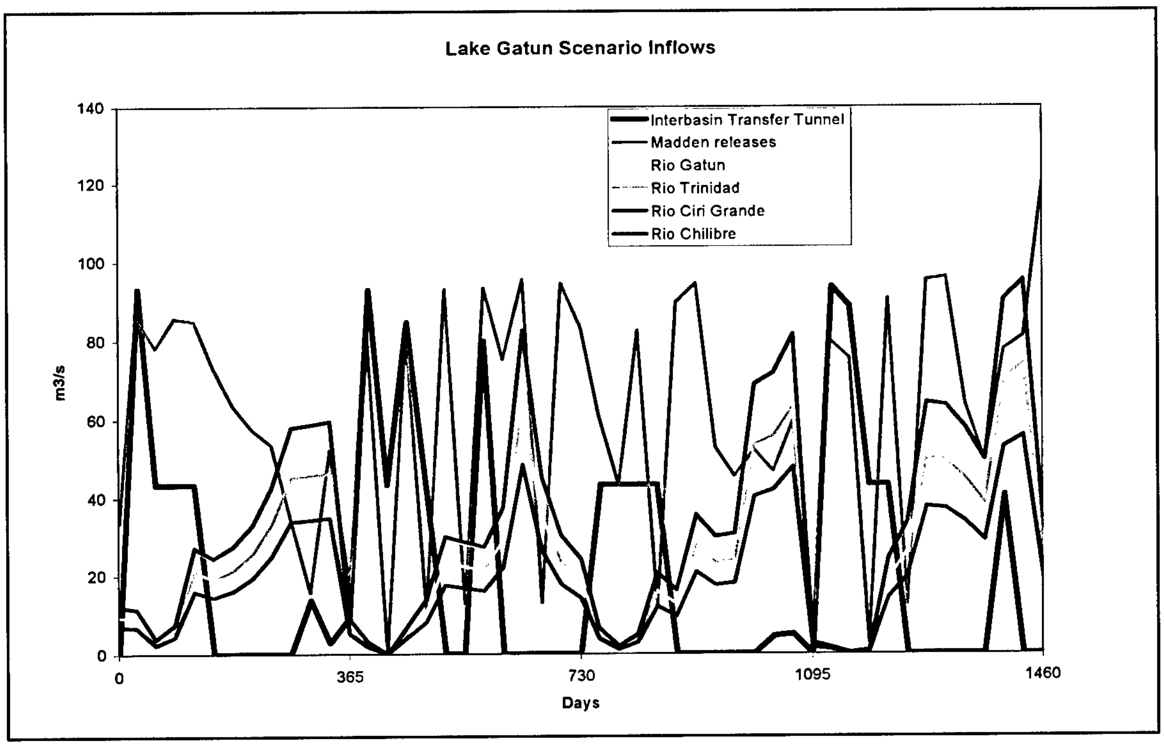

Figure 7-78. Gatun Lake scenario inflows developed from HEC-5 simulation sesults

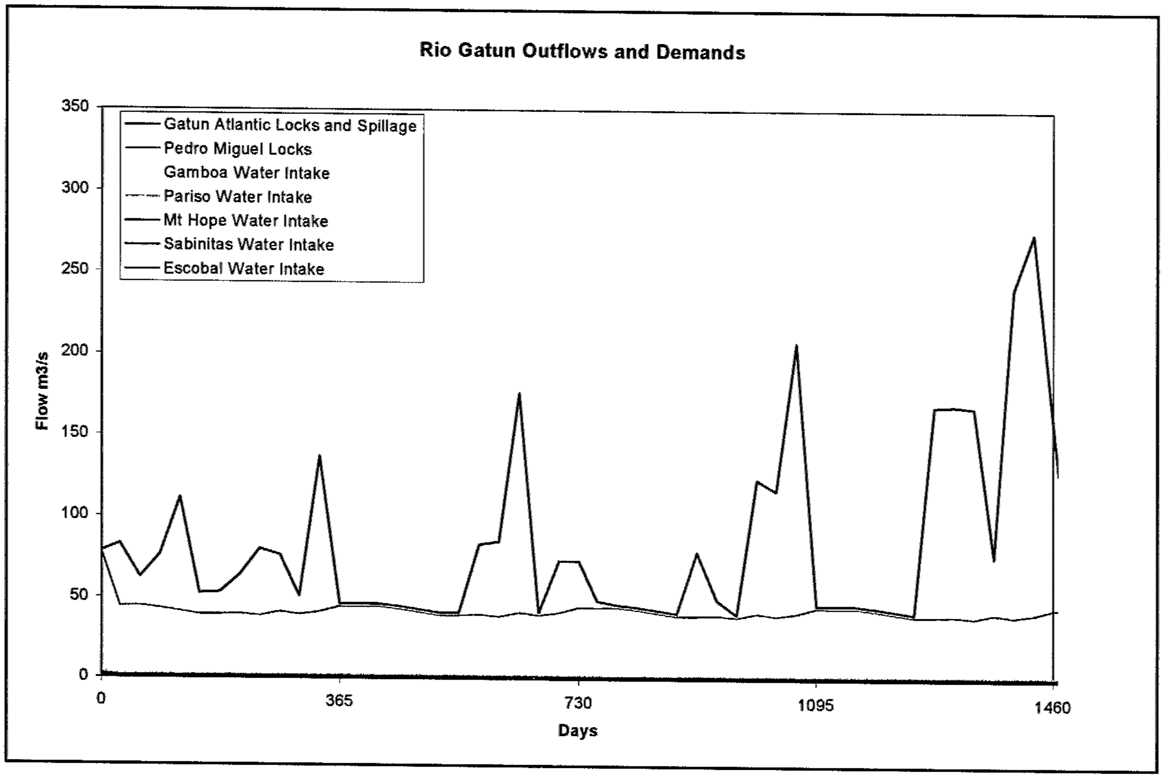

Figure 7-79. Gatun Lake outflows and demands

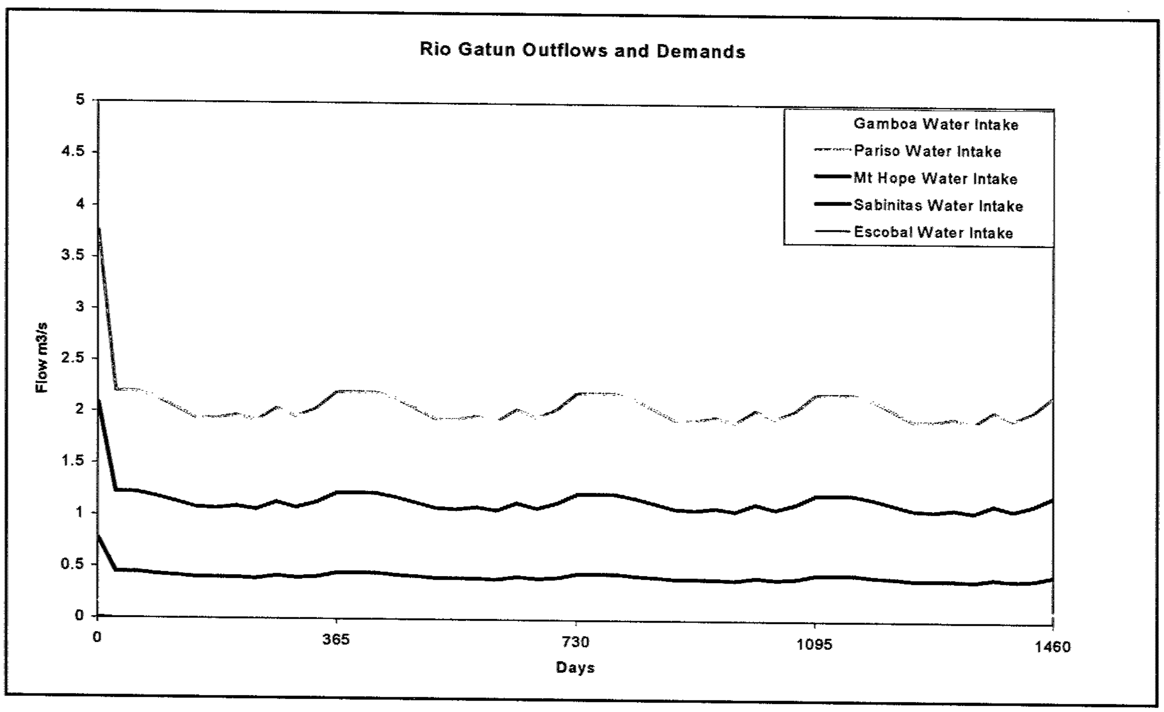

Figure 7-80. Gatun Lake water demands.

Shown in Figure 7-81 are the dissolved oxygen levels for the inter-basin transfer flow intakes and the flows the two scenarios where water was transferred to Gatun Lake from Rio Indio Reservoir. Shown in Figure 7-82 are temperatures for the inter-basin transfer flow intakes and the flows the two scenarios where water was transferred to Gatun Lake from Rio Indio Reservoir. It is evident in these figures that the dissolved oxygen concentrations at the inter-basin transfer tunnel intakes follow similar patterns whether one or multi-port withdrawals are used. The dissolved oxygen levels at the intake tend to be lower for the single level case as would be expected since the multi-level case blends waters from higher in the water column with higher dissolved oxygen levels. For the multi-level intake case, the dissolved oxygen levels can be from 0.5 to 1.0 mg/l higher than the single-level case. However, what must be considered are what the dissolved oxygen levels are when the tunnel is in operation. During period of tunnel operation, the differences in the dissolved oxygen levels for the tunnel waters much less. This is a result of the mixing in Rio Indio Reservoir resulting from the high transfer flow rates. The greatest deviation between the dissolved oxygen levels at the intakes occurs at times when no transfer is occurring and the reservoir is filling. Consequently, the critical time for potential passage of low dissolved oxygen water in these scenarios are when the inter-basin transfer flows begin and before the resulting mixing in Rio Indio has had a significant impact.

Intake temperature conditions for the single level and multi-level case show similar results. The single level intake case had periods of slightly cooler temperatures (0.5-1.0 °C). During other periods, the differences between the two

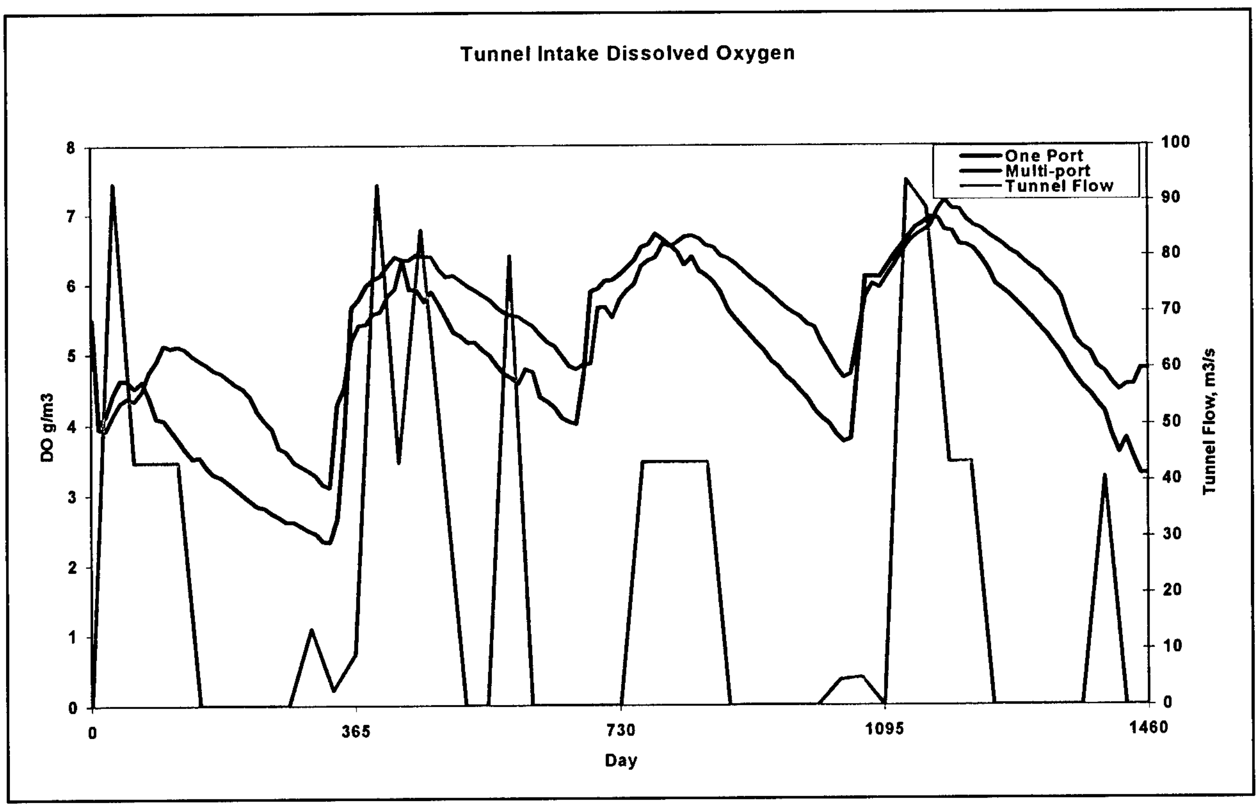

Figure 7-81. Inter-basin tunnel scenario dissolved oxygen concentrations

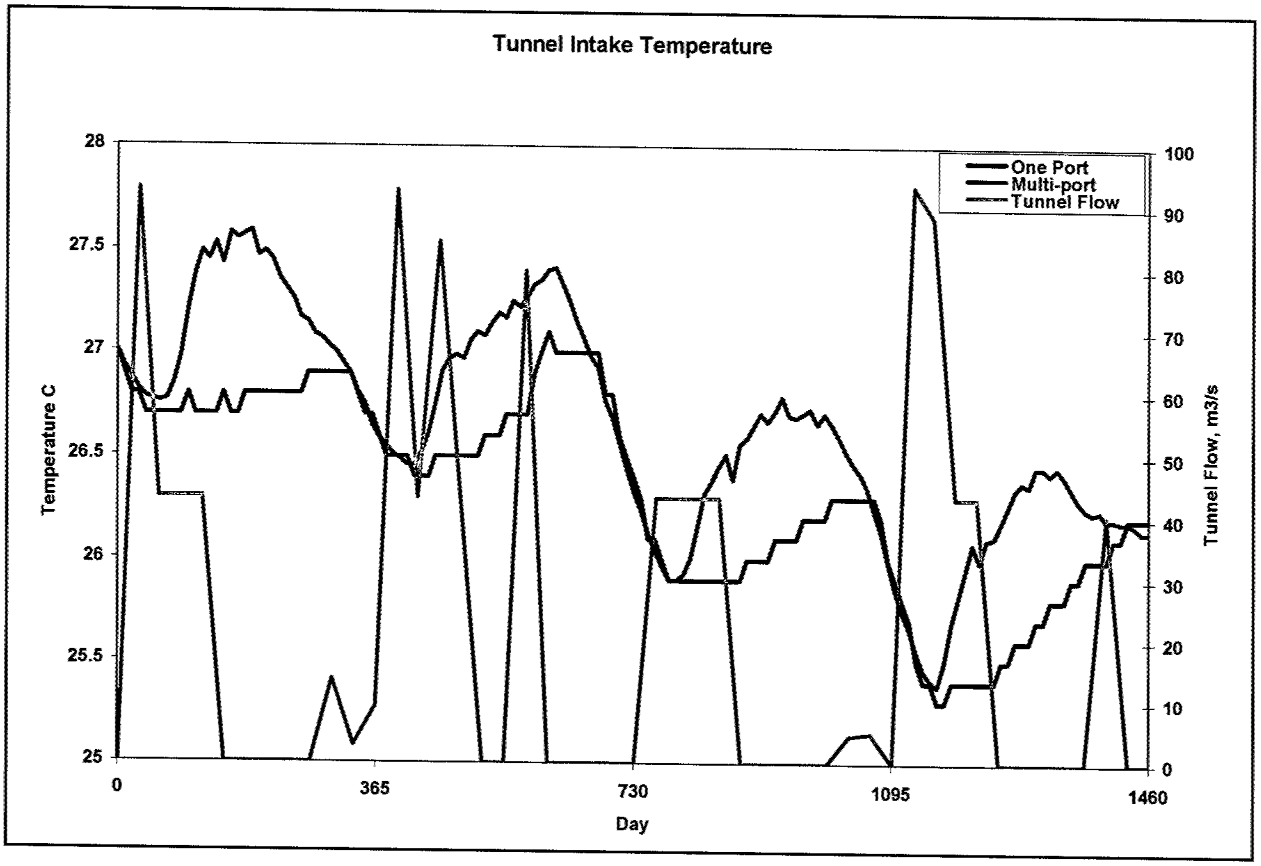

Figure 7-82. Inter-basin tunnel scenario temperatures

scenarios were negligible. The greatest difference corresponded to times when there was no inter-basin transfer and the only flows through Rio Indio Reservoir were the regulatory releases. During these periods the reservoir was filling and conditions at the tunnel intake sites the most quiescent which resulted in the vertical temperature variation at the intake site.

From the temperature and dissolved oxygen levels at the tunnel intakes, it is evident that the tunnel waters had similar conditions for both scenarios. No allowance was made when specifying the tunnel discharge boundary conditions to account for water temperature change in the tunnel between the intake and the discharge sites. Nor was an allowance made for reaeration at the tunnel outfall resulting from flow collision with baffle blocks.

Model results

As the item of concern in these scenarios was the water quality at the Gatun Lake M&I water intakes, results for these scenarios are limited to those locations. Time series information is recorded for all withdrawal locations in W2. This information represents the water quality condition of the water that is "entering the pipe." Shown in Figures 7-83 through 7-87 are the dissolved oxygen levels for the five water intake locations included in the model. It is obvious that there

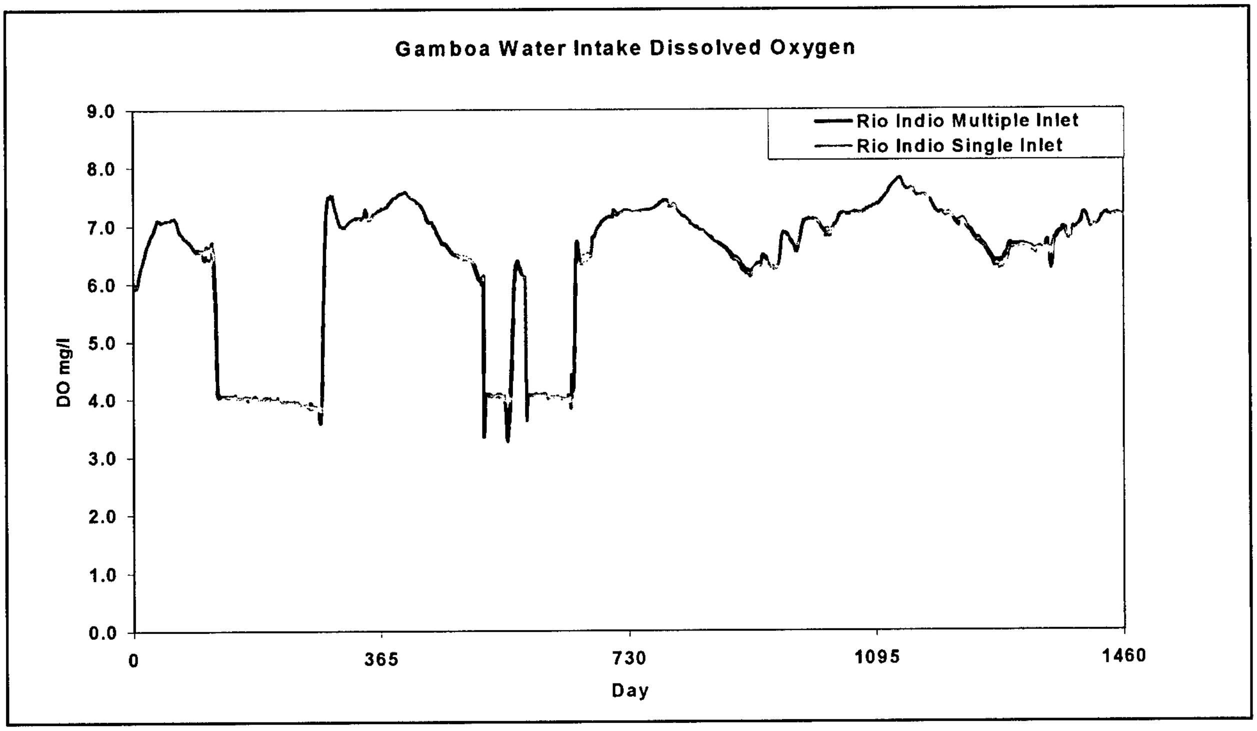

Figure 7-83. Gamboa water intake dissolved oxygen.

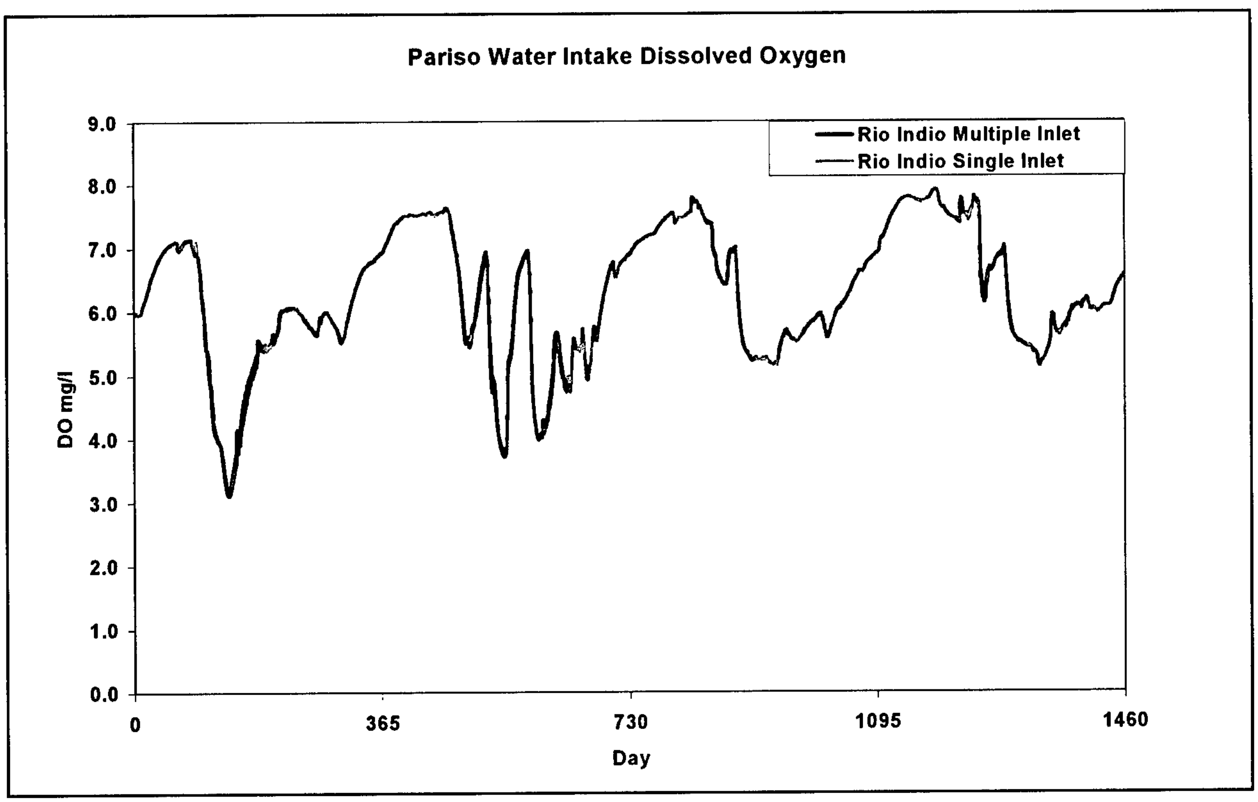

Figure 7-84. Parisio water intake dissolved oxygen

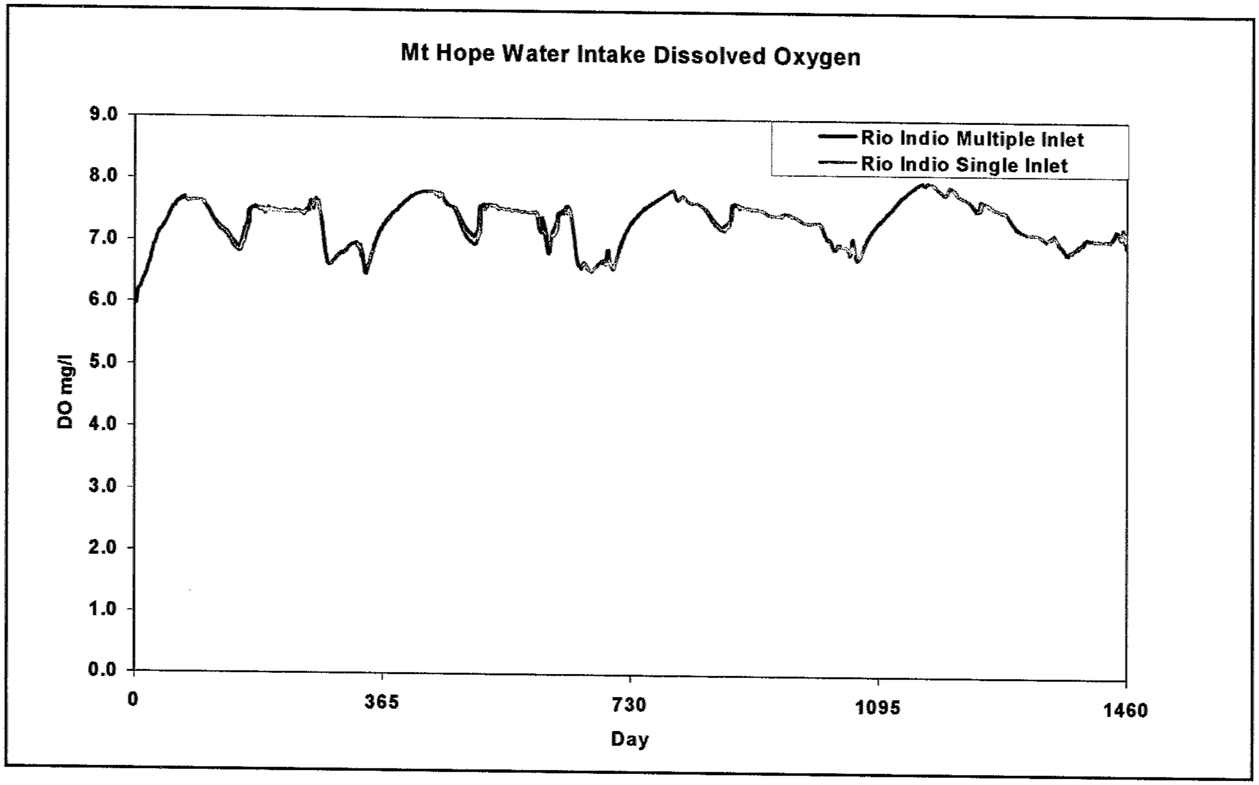

Figure 7-85. Mt. Hope water intake dissolved oxygen

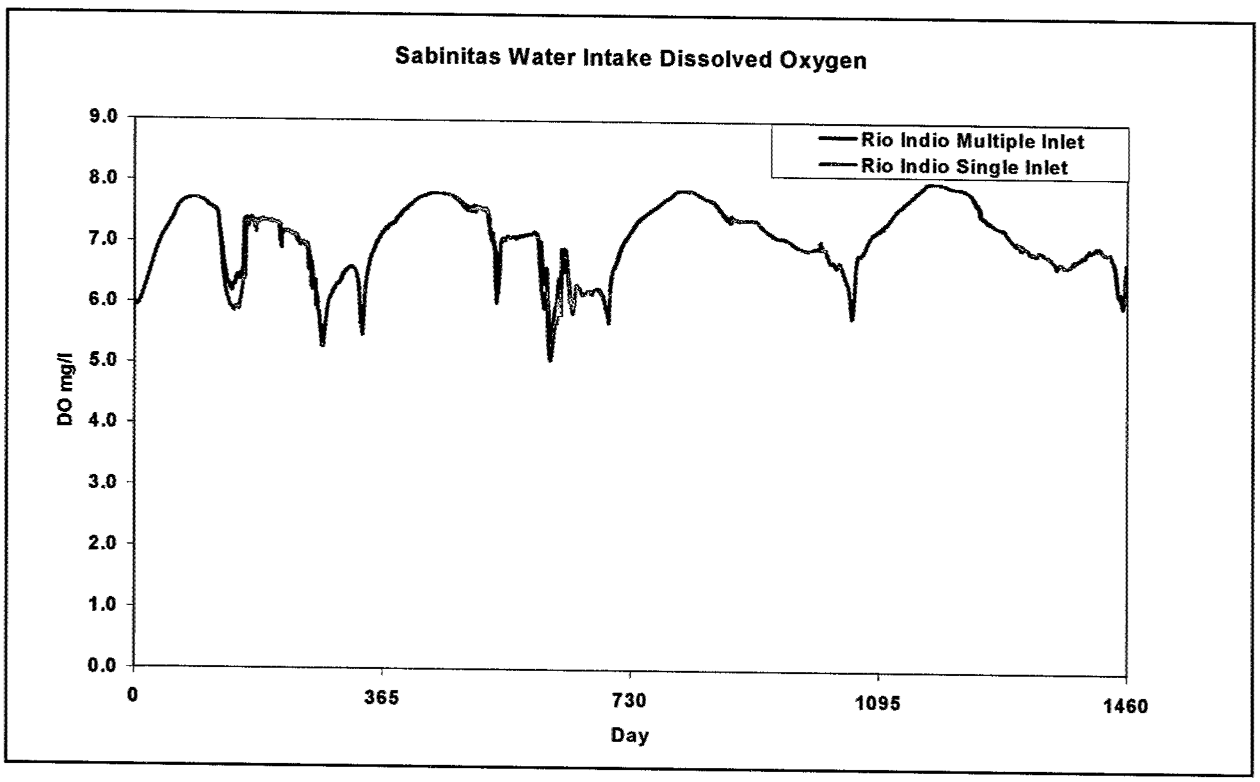

Figure 7-86. Sabinitas water intake dissolved oxygen

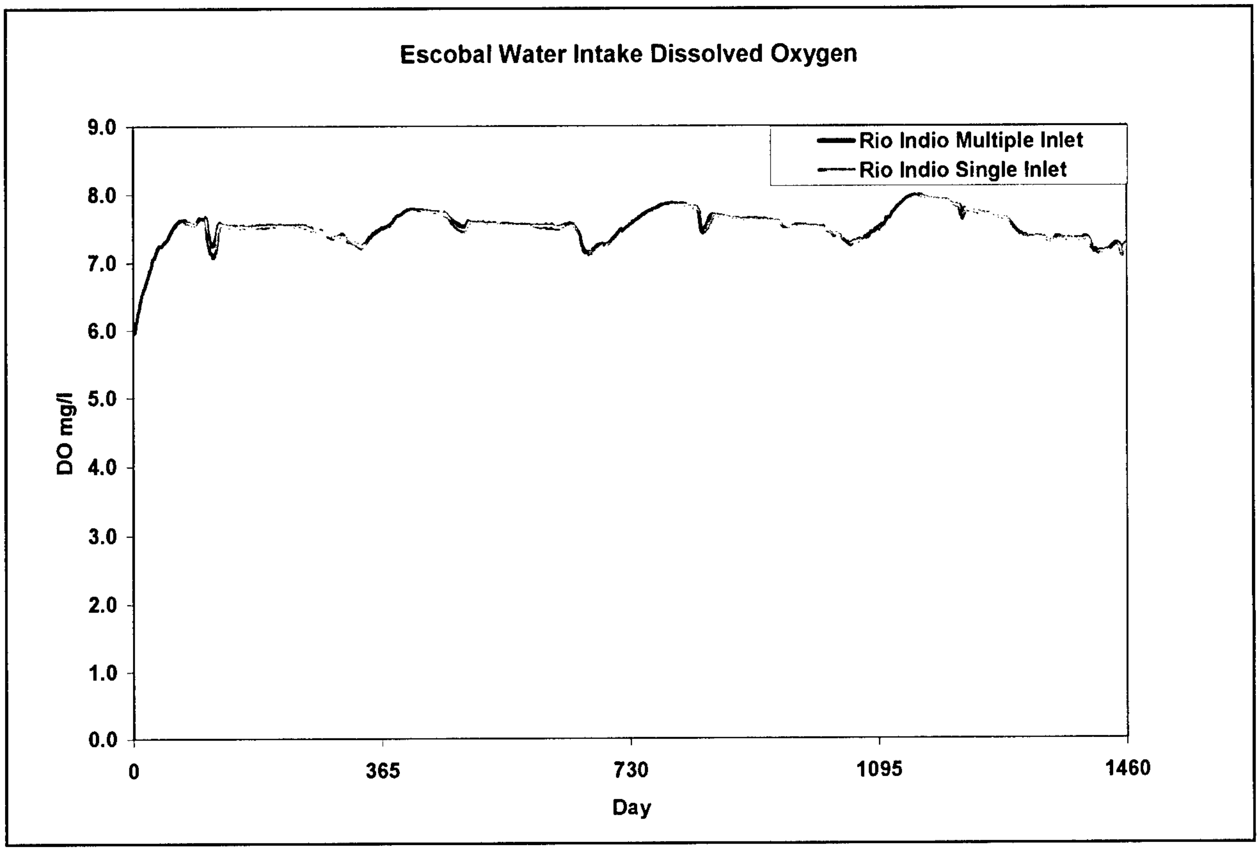

Figure 7-87. Escobal water intake dissolved oxygen

is little difference in water quality conditions between the two scenarios(i.e., single tunnel intake at 32 m el. and multiple tunnel intakes). This is reasonable as the only differences in the composition of the simulations are the concentrations in the inter-basin transfer flow.

Shown in Figure 7-88 is a longitudinal view of the western branch, branch 4, of the Gatun Lake W2 grid. Indicated on this figure are the segments where the tunnel inflows are placed and the segment containing the Escobal water intake. Shown in Figures 7-89 through 7-93 are the dissolved oxygen levels in this branch for the case with a single inter-basin transfer tunnel inlet in the Rio Indio Reservoir. Shown in Figures 7-94 through 7-98 are similar figures for the case with multiple inter-basin transfer tunnel inlets in the Rio Indio Reservoir. With each figure are hydrographs of the total inter-basin transfer flow which indicate the time that the figure corresponds to in the simulation. The figures shown here for Gatun Lake represent the dissolved oxygen conditions at approximately the same time as those shown for Rio Indio.

Dissolved oxygen levels in Gatun Lake are similar for both cases. Overall the water column is well mixed with high dissolved oxygen levels throughout. There are instances of anoxia in the bottom of the branch which are due to the SOD. These episodes were indicated by the observed data used for model calibration. The upper end of branch 4 was one of the few locations that demonstrated some dissolved oxygen stratification.

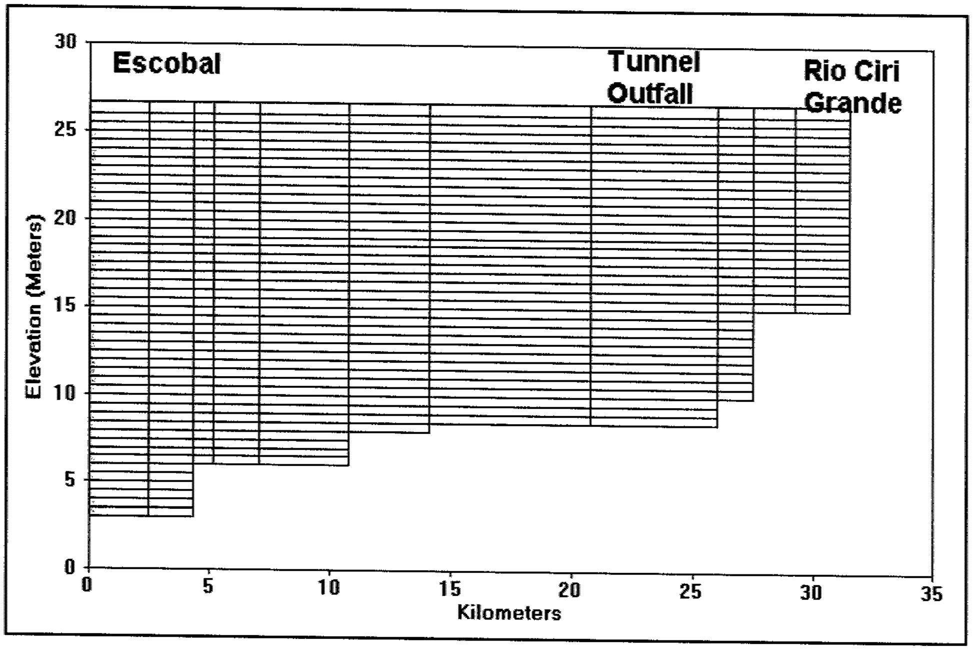

Figure 7-88. Gatun Lake western branch

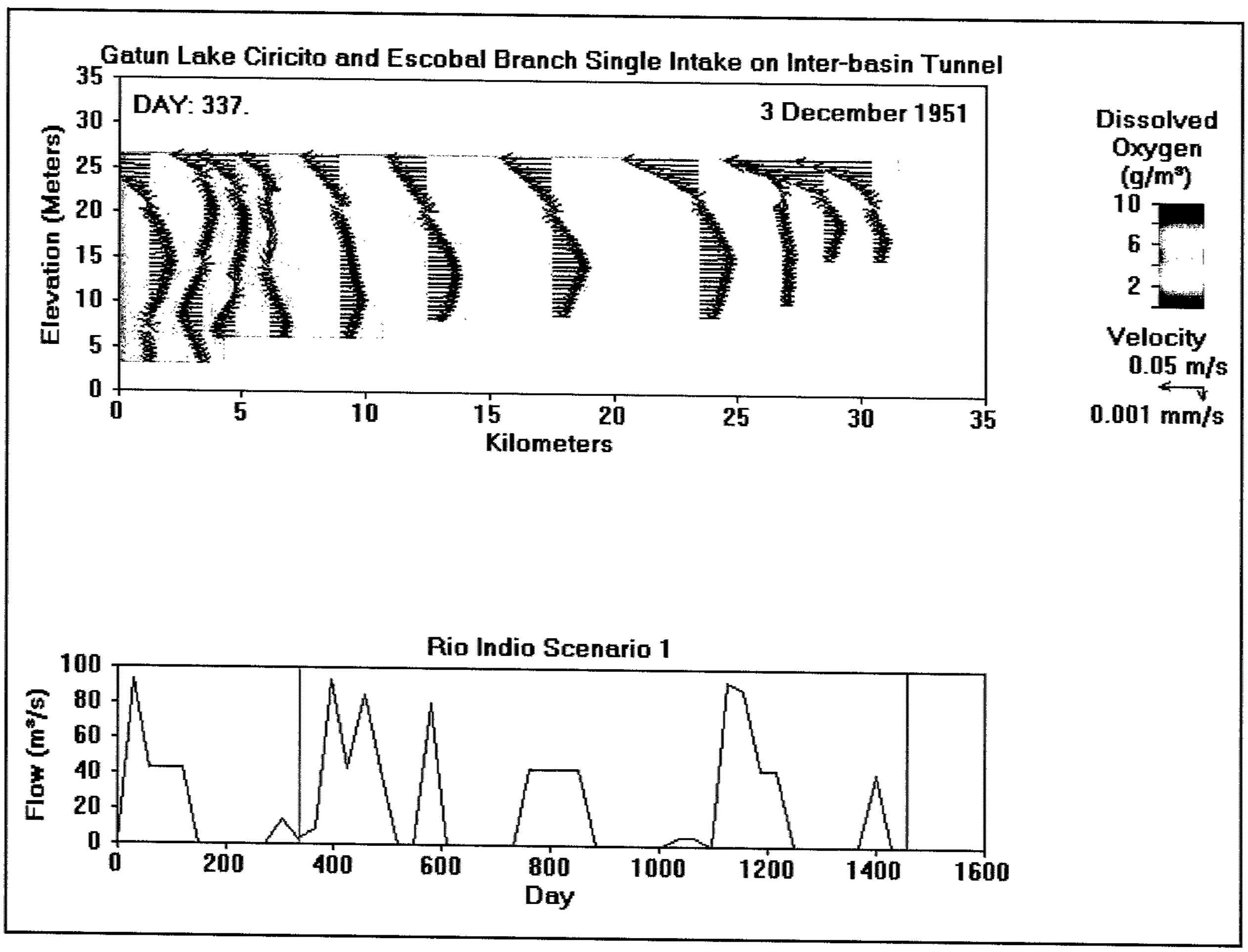

Figure 7-89. Gatun Lake dissolved oxygen at day 337 of simulation, single tunnel inlet

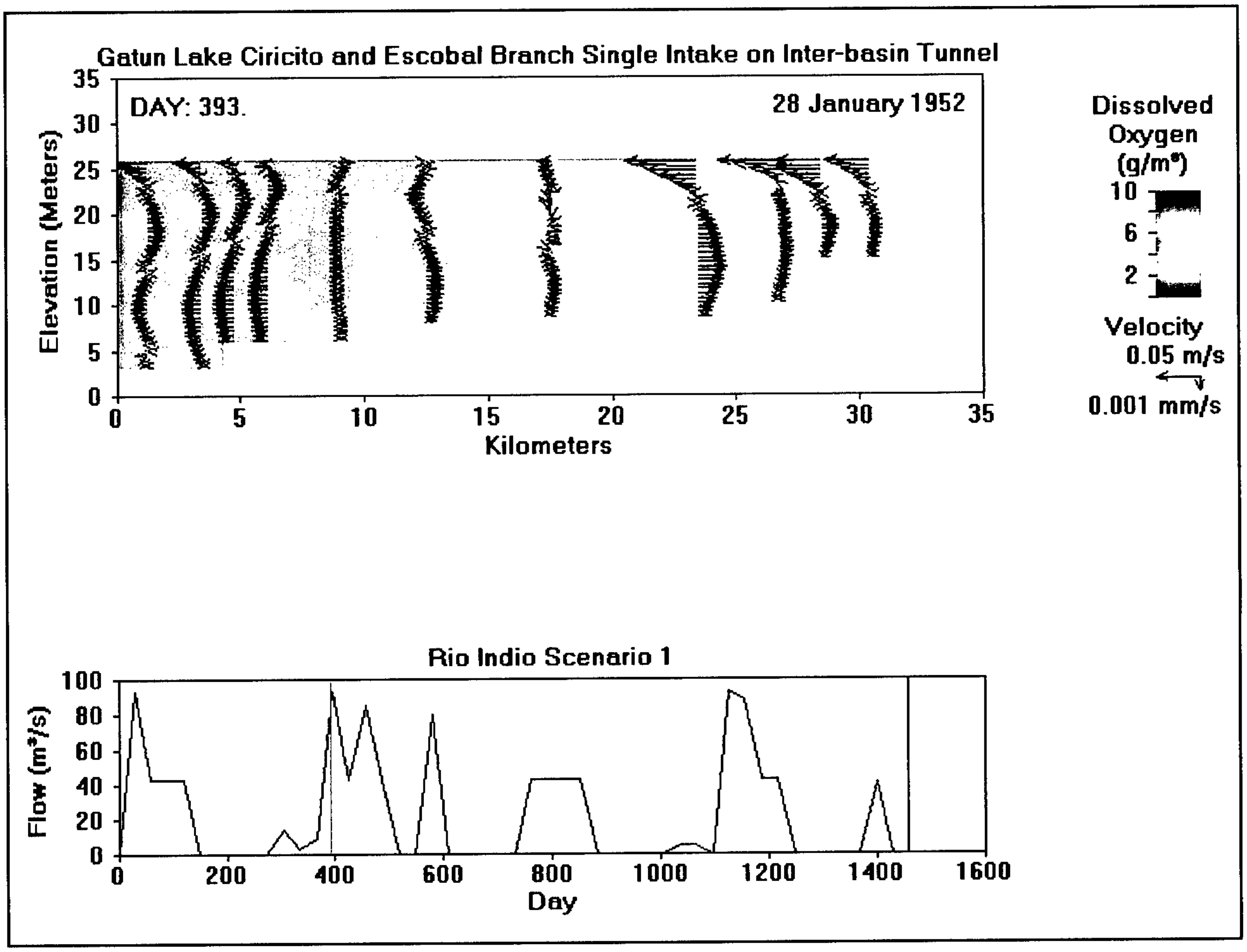

Figure 7-90. Gatun Lake dissolved oxygen at day 393 of simulation, single tunnel inlet

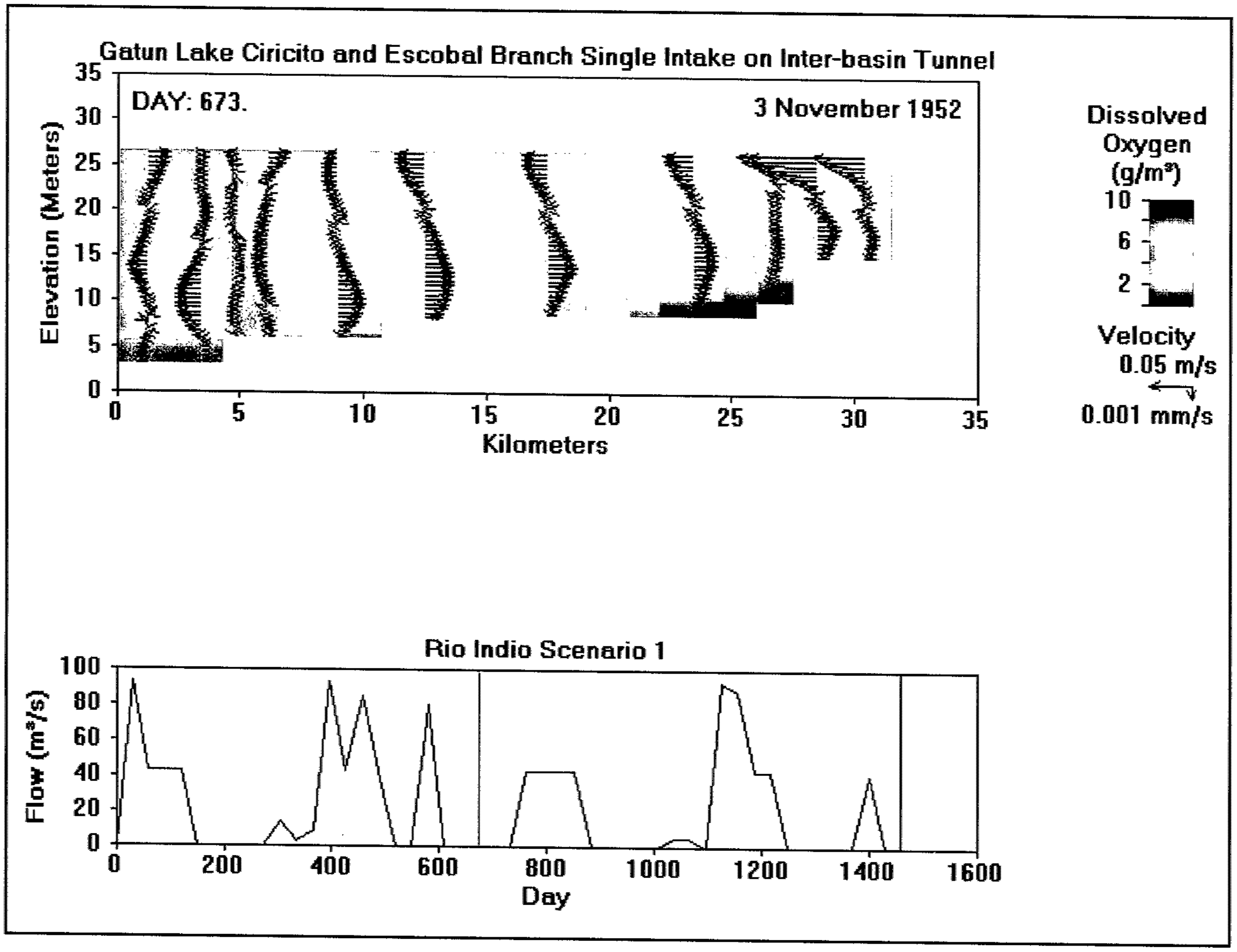

Figure 7-91. Gatun Lake dissolved oxygen at day 673 of simulation, single tunnel inlet

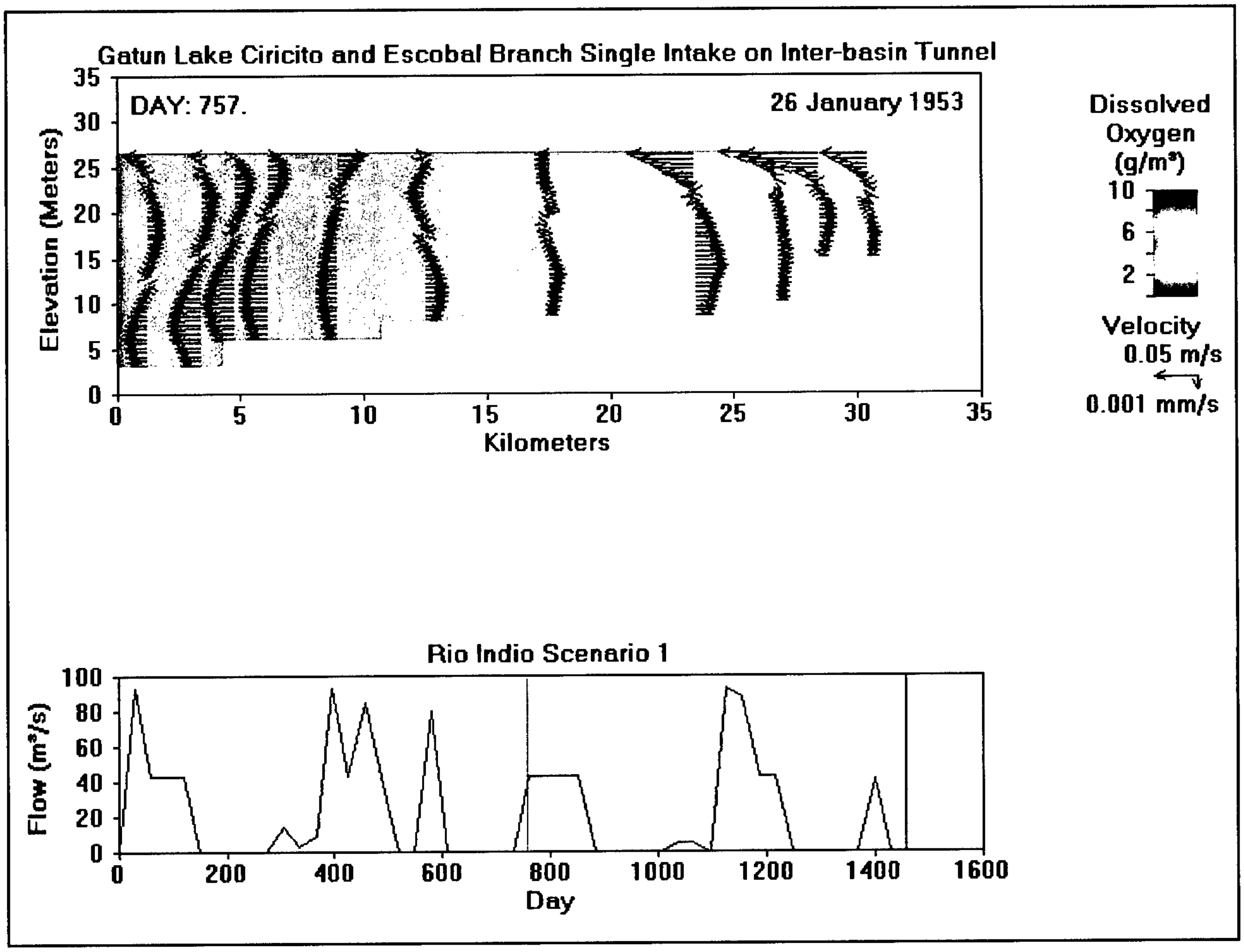

Figure 7-92. Gatun Lake dissolved oxygen at day 757 of simulation, single tunnel inlet

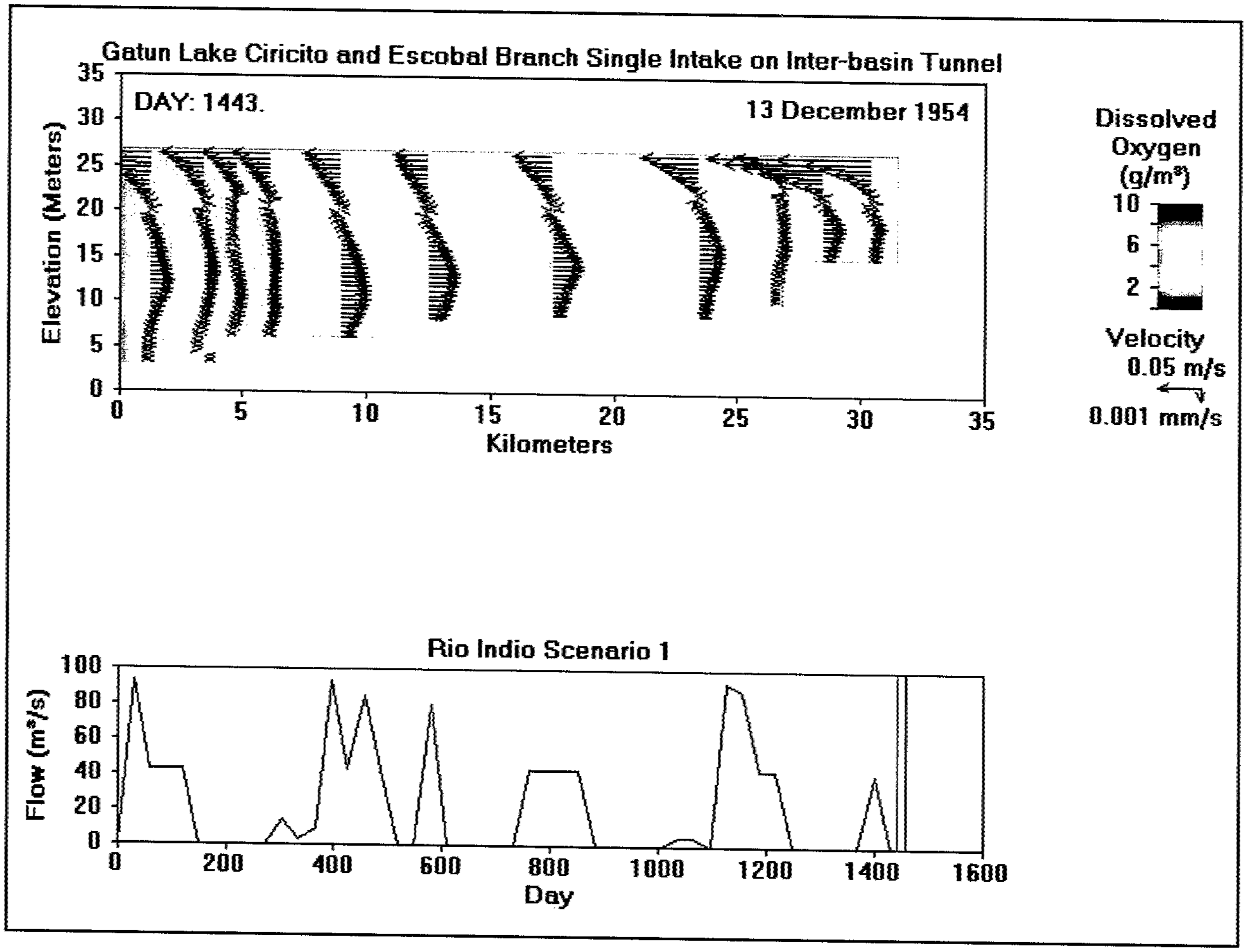

Figure 7-93. Gatun Lake dissolved oxygen at day 1443 of simulation, single tunnel inlet

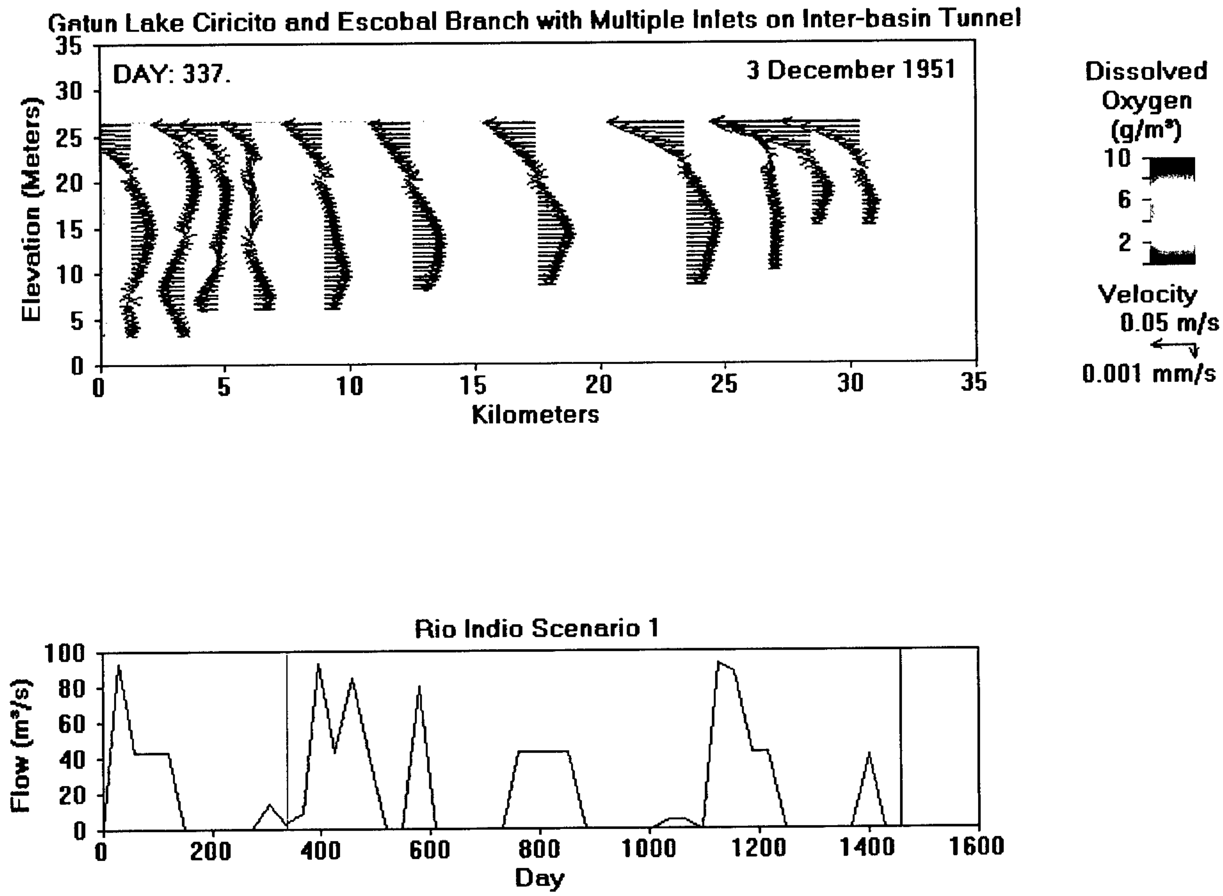

Figure 7-94. Gatun Lake dissolved oxygen at day 337 of simulation, multiple tunnel inlets

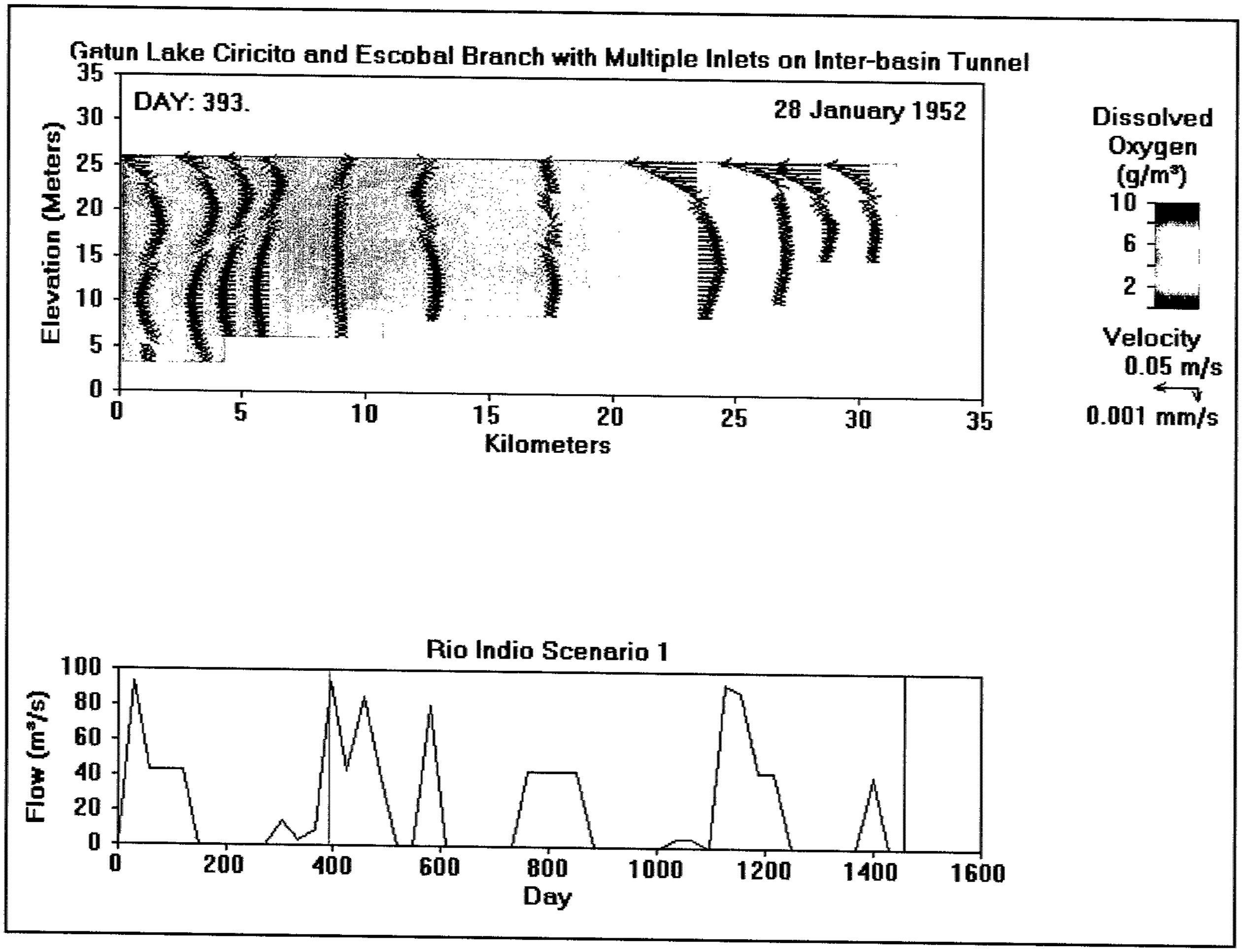

Figure 7-95. Gatun Lake dissolved oxygen at day 393 of simulation, multiple tunnel inlets

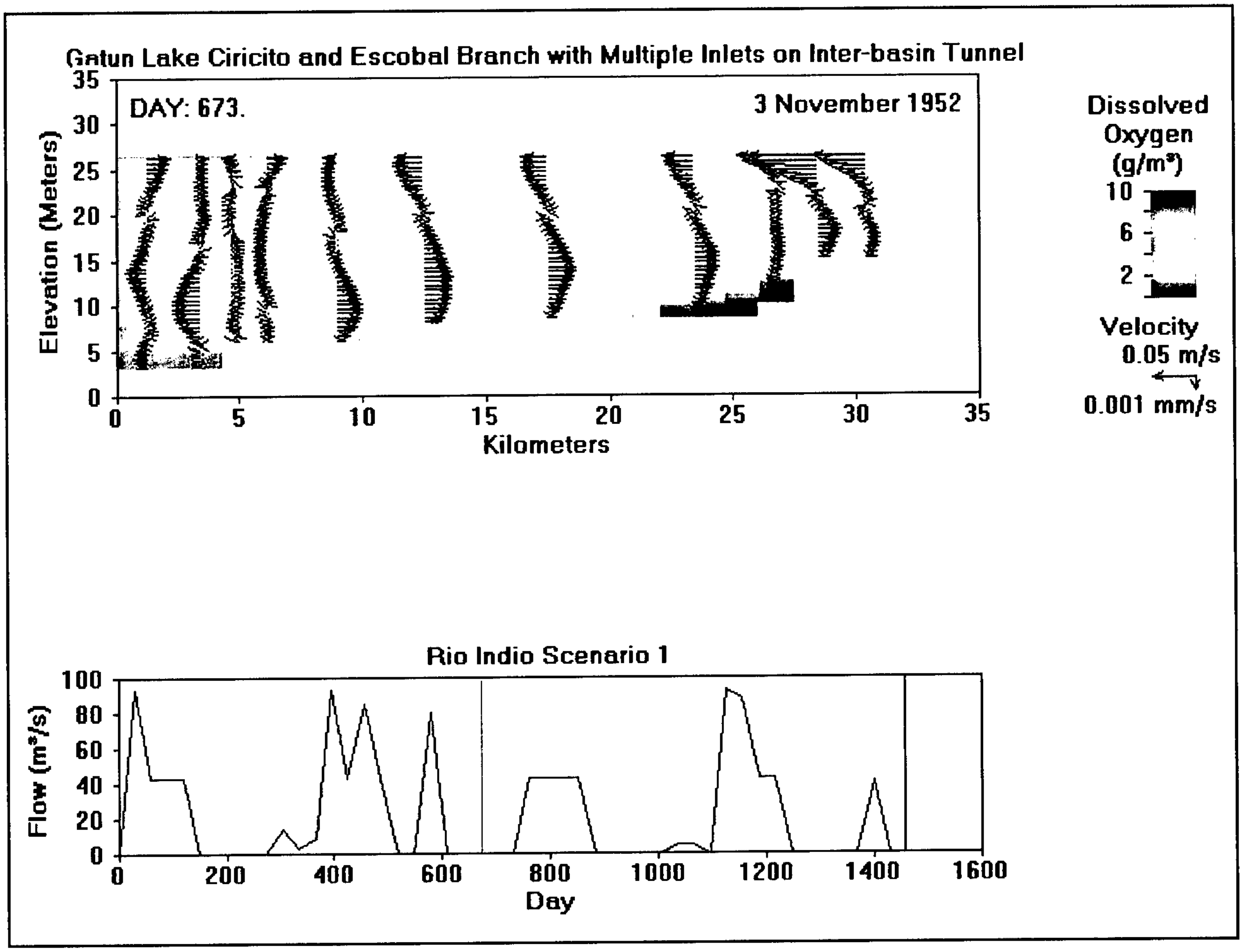

Figure 7-96. Gatun Lake dissolved oxygen at day 673 of simulation, multiple tunnel inlets

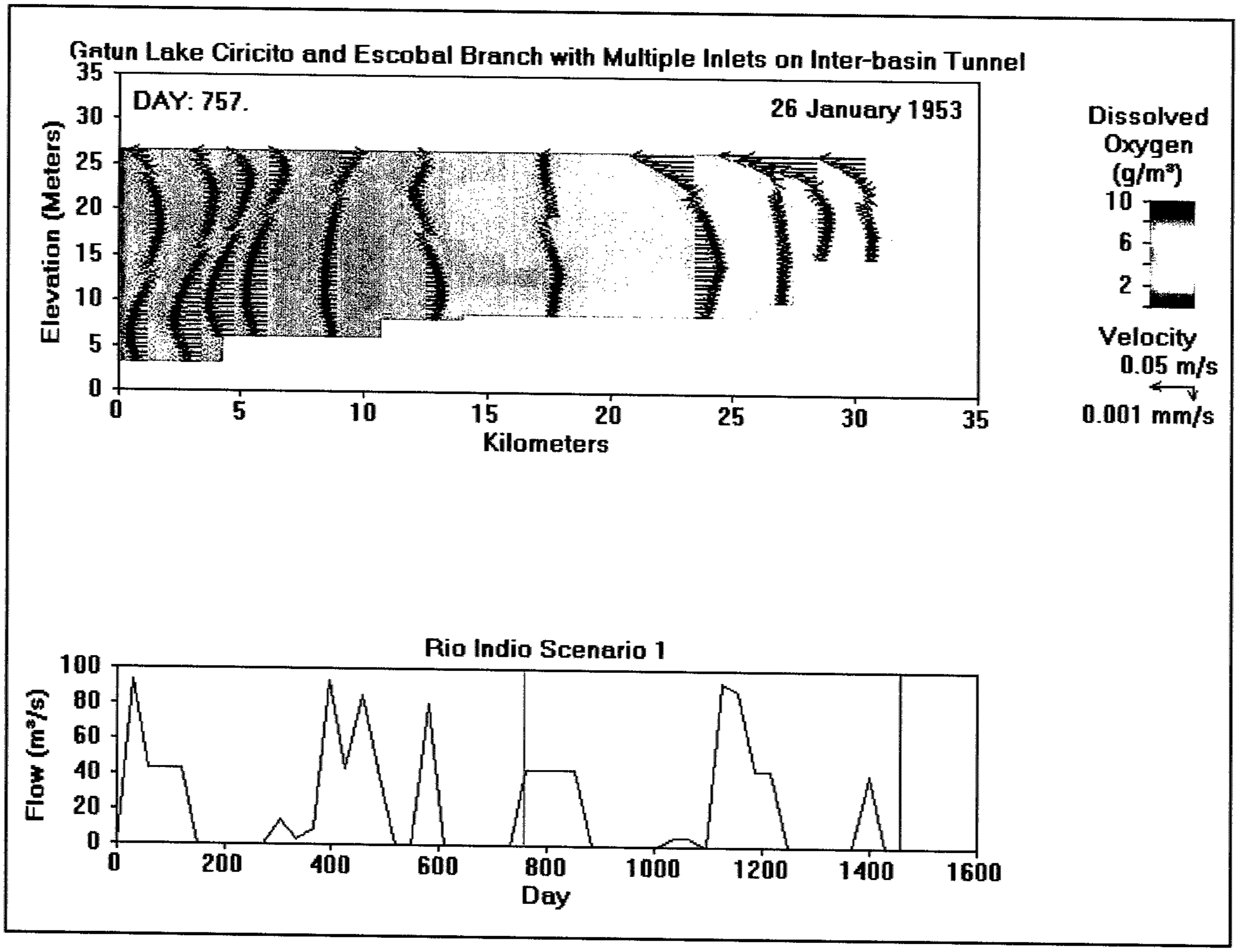

Figure 7-97. Gatun Lake dissolved oxygen at day 757 of simulation, multiple tunnel inlets

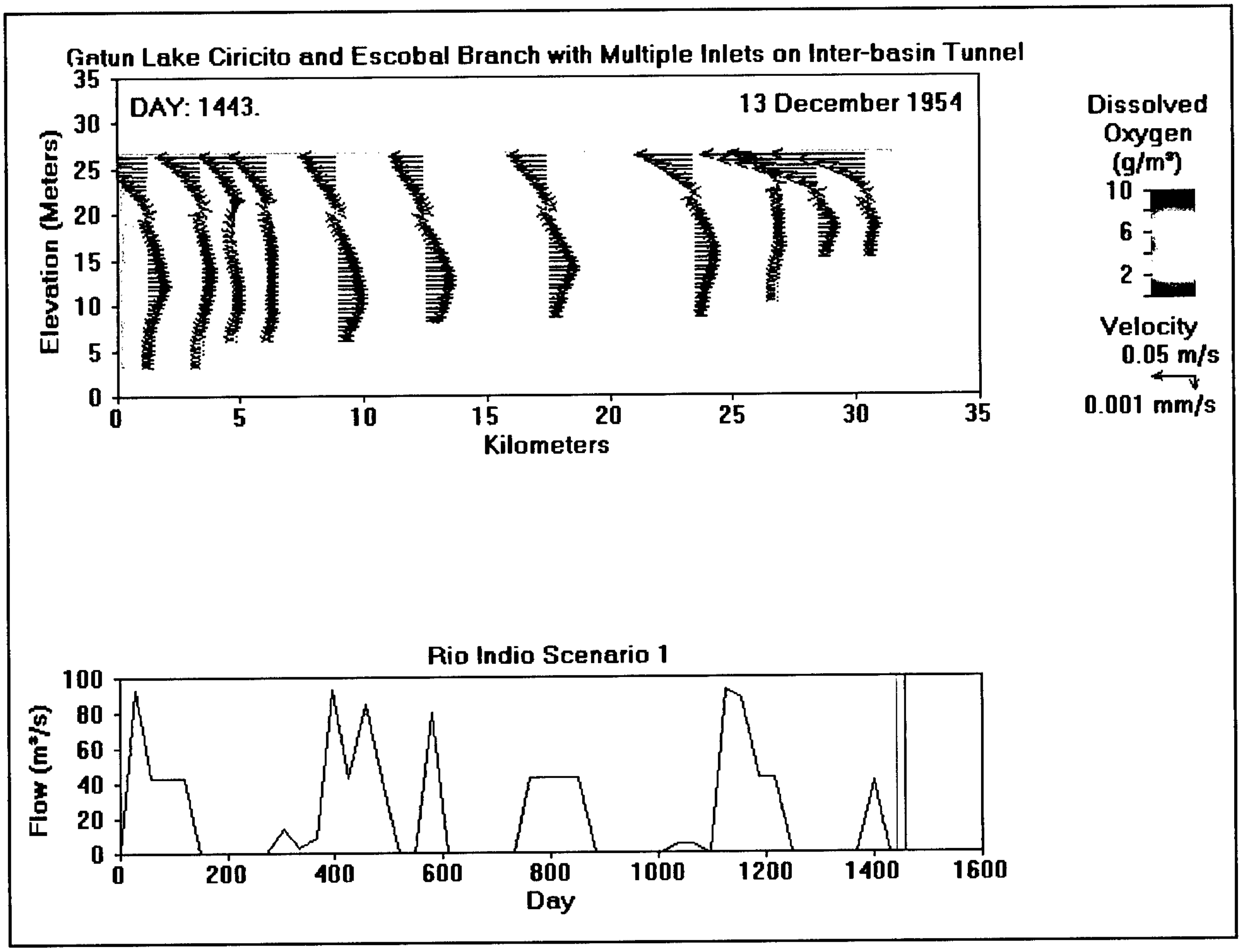

Figure 7-98. Gatun Lake dissolved oxygen at day 1443 of simulation, multiple tunnel inlets

Caño Sucio

W2 modeling of Caño Sucio is on hold awaiting scenario definition. Presented here are the current model configuration. Additional modeling results for Caño Sucio will be presented in future revisions to this document

The proposed reservoir for Caño Sucio is shown in Figure 7-99. Caño Sucio will have only one branch with 23 segments, Figure 7-100. Currently W2 for Caño Sucio is under development. The volume elevation curve for Caño Sucio is shown in Figure 7-101. It is evident that the resultant bathymetry used for W2 under predicts the volume for Caño Sucio greatly. This issue will be resolved before further modeling continues with Caño Sucio.

Coclé del Norte

W2 modeling of Coclé del Norte is on hold awaiting scenario definition. Presented here are the current model configuration. Additional modeling results for Coclé del Norte will be presented in future revisions to this document.

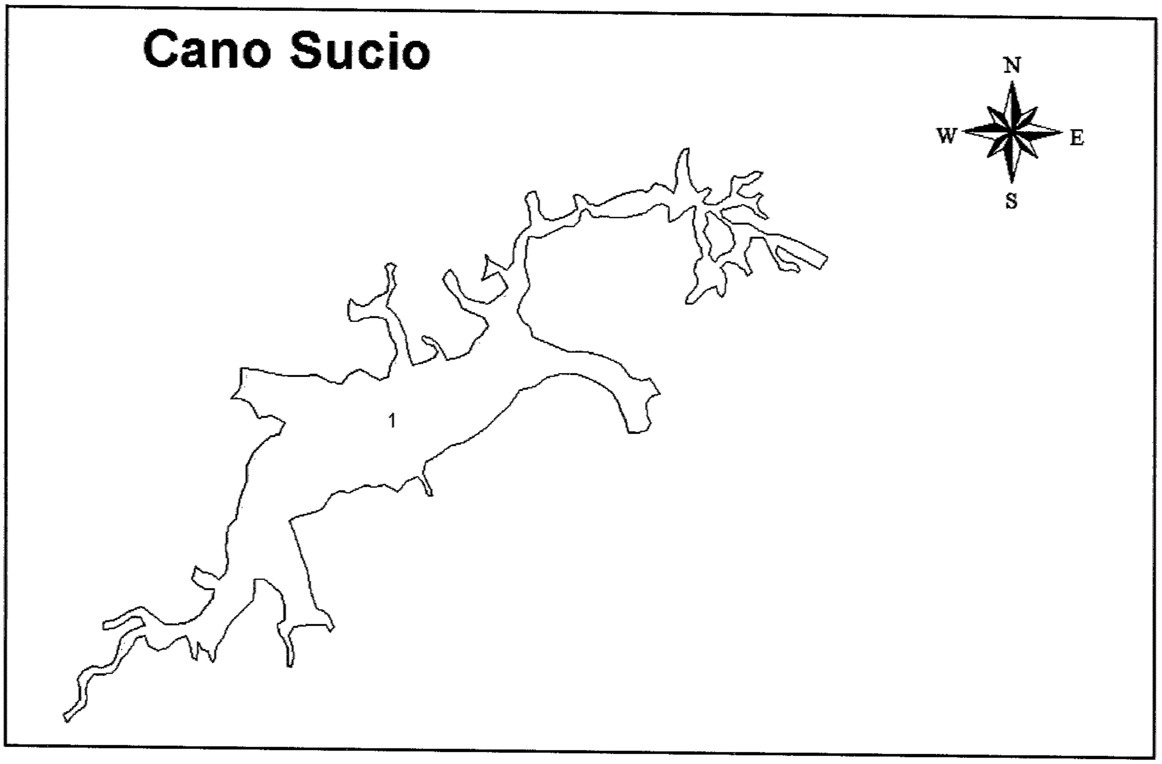

Figure 7-99. Caño Sucio branches

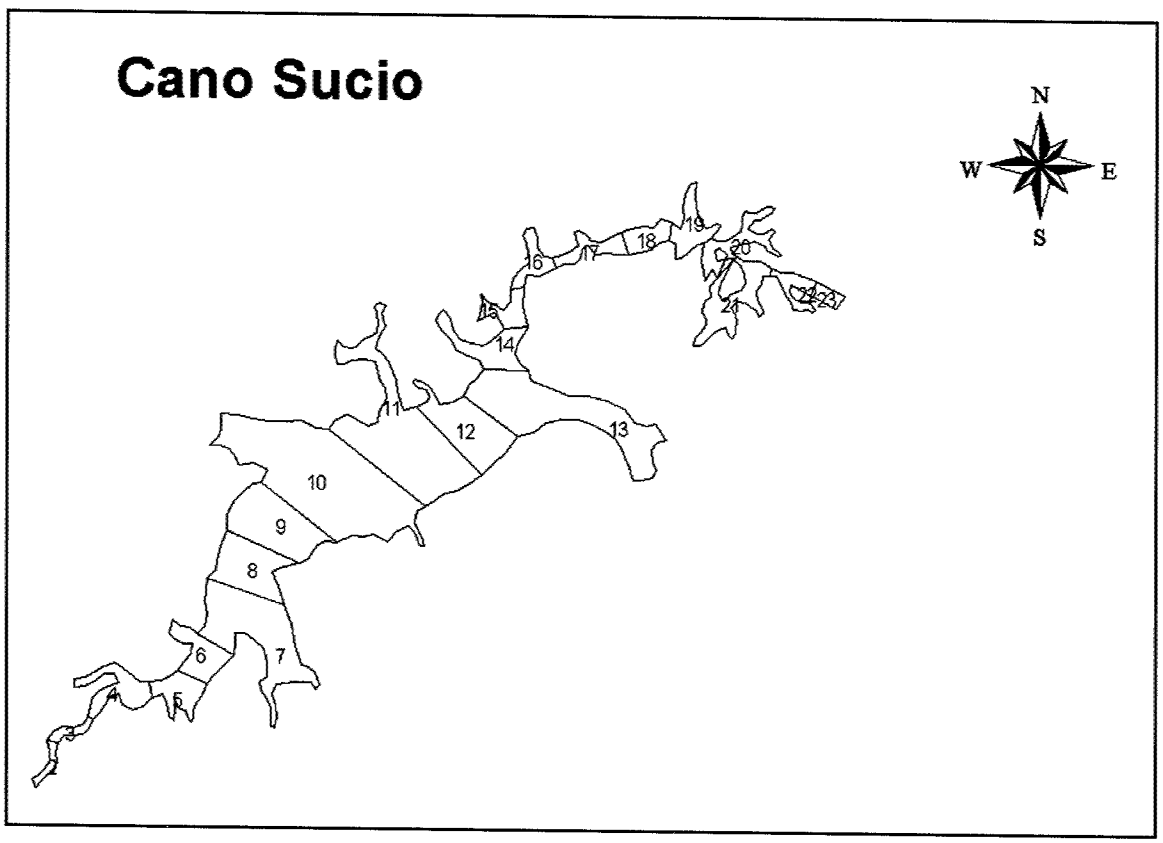

Figure 7-100. Caño Sucio segments

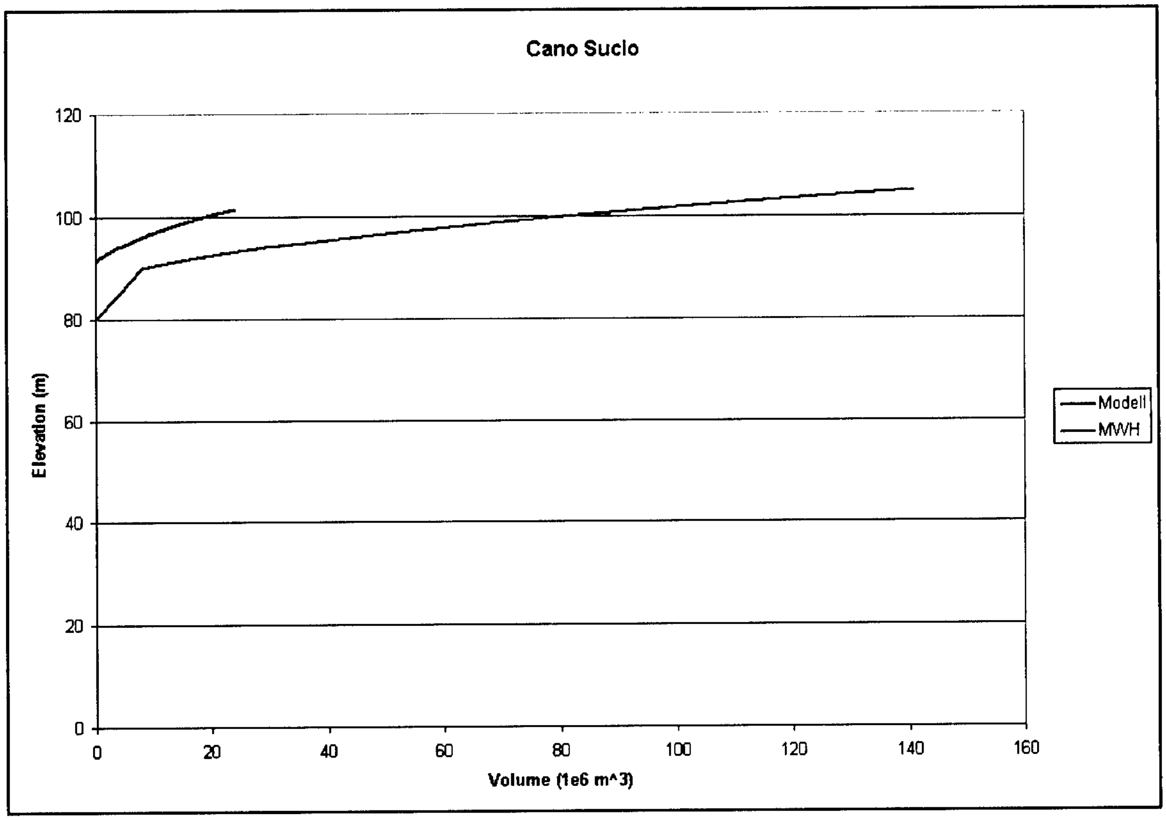

Figure 7-101. Caño Sucio volume-elevation curves

Coclé del Norte is the largest and most western of the proposed reservoirs. Waters from Coclé del Norte would be transferred via Caño Sucio or tunnels to Rio Indio and from there to Gatun. As currently configured for W2, Coclé del Norte is represented with two branches, Figure 7-102 and 27 branches, Figure 7-103. The W2 volume elevation curve for Coclé del Norte is shown in Figure 7-104. The shapes of the W2 volume-elevation curve and the reported curve are very similar except for the vertical offset. The difference is due to specification of too high a bottom elevation in W2. This will be corrected prior to additional modeling with Coclé del Norte.

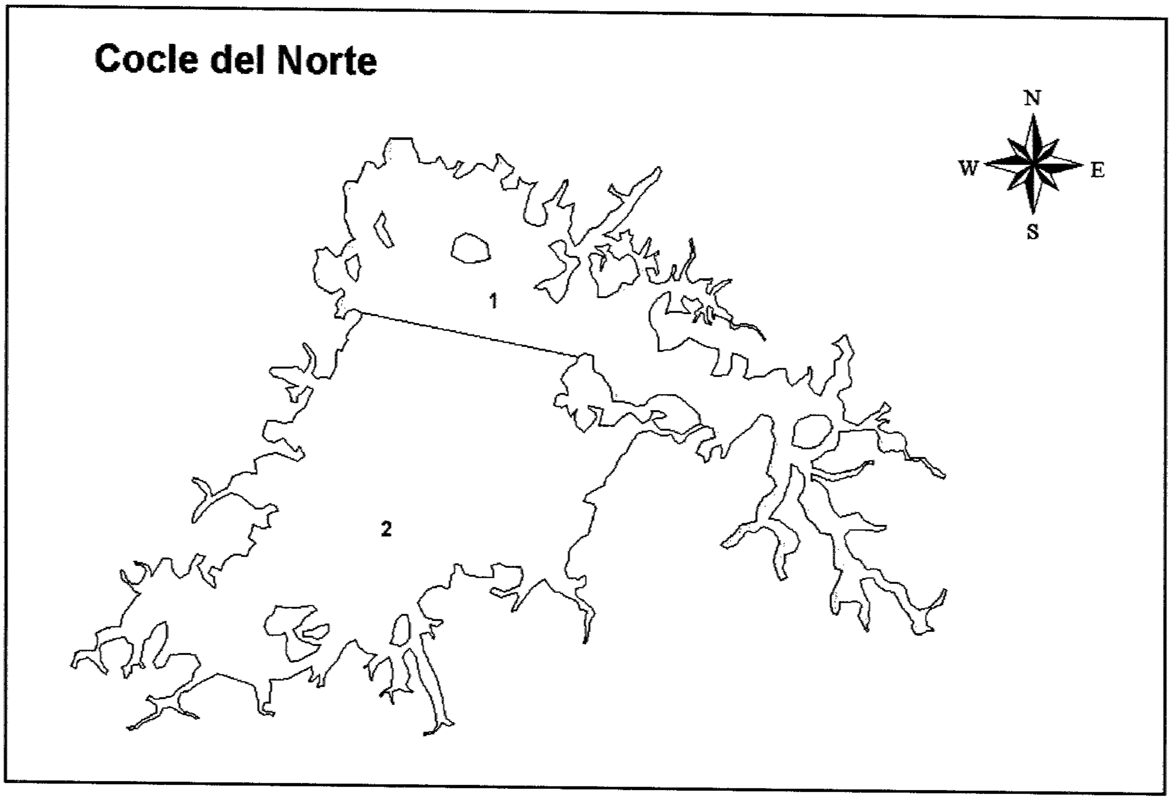

Figure 7-102. Coclé del Norte banches

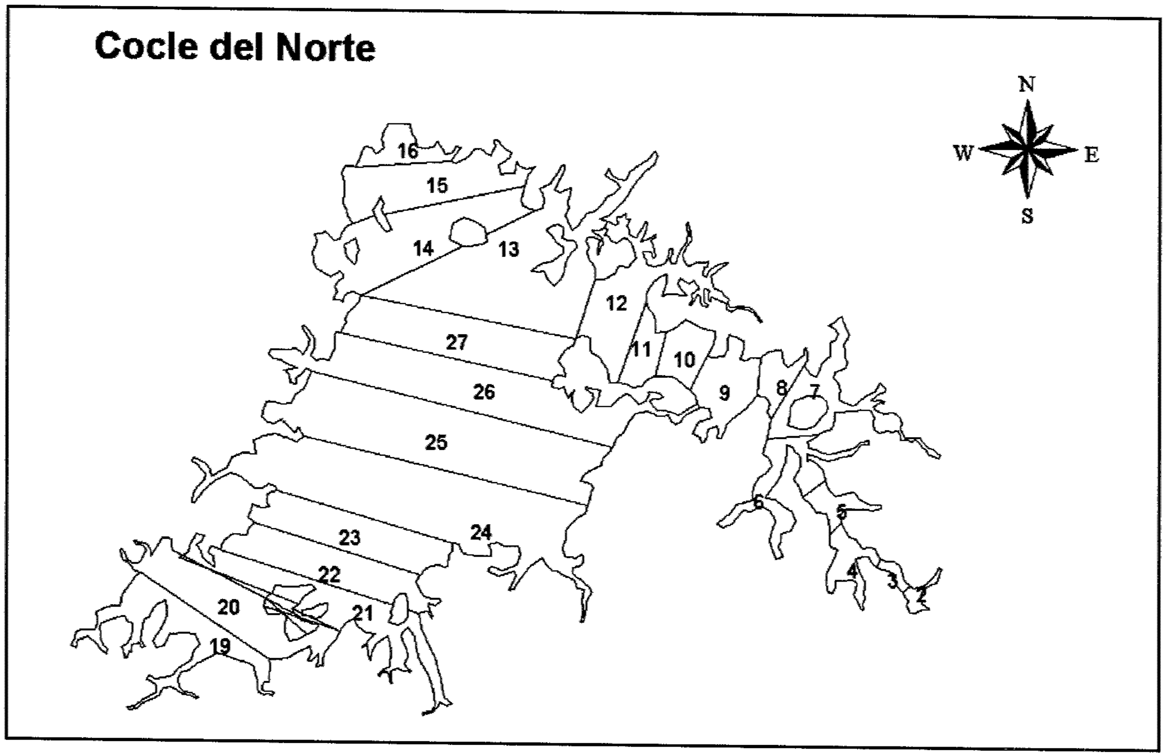

Figure 7-103. Coclé del Norte segments

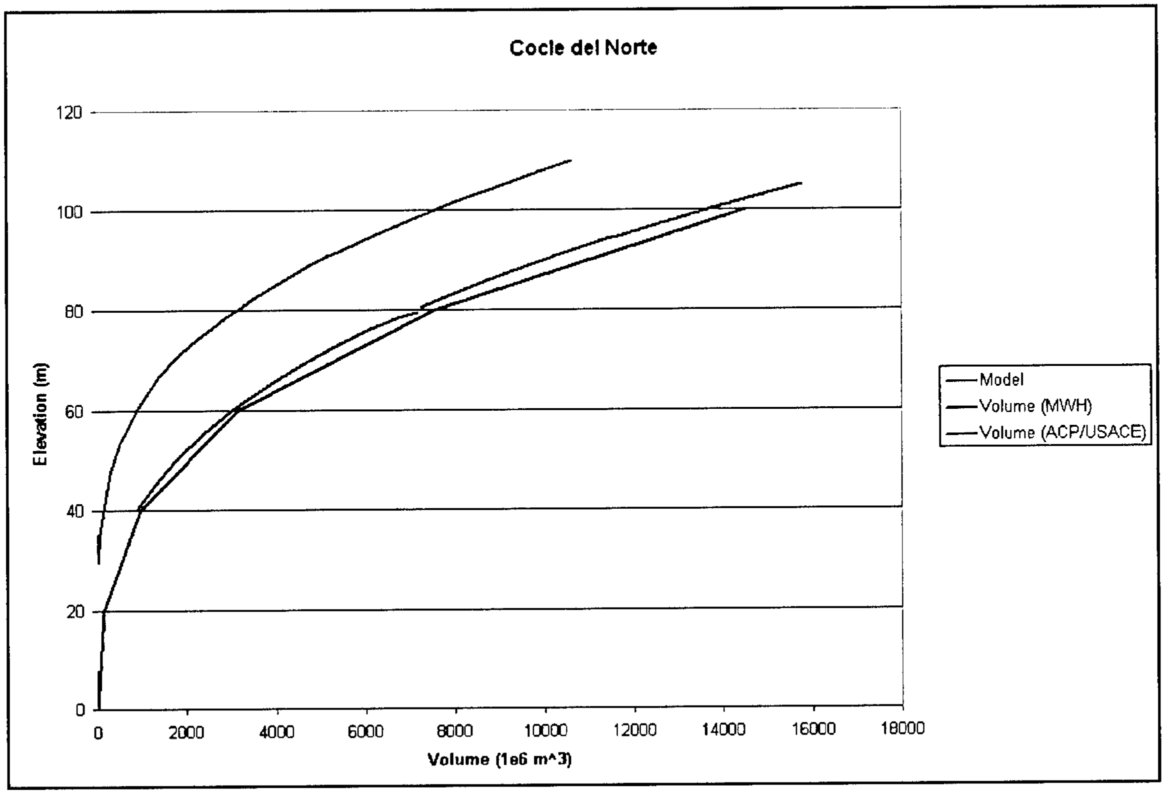

Figure 7-104. Coclé del Norte volume-elevation curves

8 Summary and Recommendations

Summary

Three reservoirs of the Panama Canal system, two existing and one proposed, were simulated using CE-QUAL-W2 for the purpose of assessing water quality impacts resulting from inter-basin transfers. Of specific concern was the impact that waters removed from the proposed Rio Indio reservoir via a tunnel would have upon water intakes when released into Gatun Lake.

CE-QUAL-W2, a two-dimensional, laterally averaged hydrodynamic and water quality model was selected as the model for performing this study based upon its capabilities for simulating reservoir operations. W2 allowed for representation of variations in water quality and currents in the longitudinal and vertical directions. A separate application of W2 was required for each reservoir. W2 was also set up for the proposed Coclé del Norte and Caño Sucio reservoirs but no simulation made. Although W2 utilizes a laterally averaged approach to modeling, it was the best choice for this study. W2 has features required to accurately simulate reservoir operations (intakes, density placed inflows, selective withdrawal) that are not found in three dimensional models developed for use in estuarine systems. Additional effort would be required to attempt to incorporate these features when there is currently no evidence that a three dimensional model is justified. In addition, a three dimensional model developed for this system based on the same data used for this W2 study would likely have produced no better results. W2 has been applied in approximately 400 water quality studies of reservoirs, lakes and estuaries. While Gatun Lake would be one of the larger reservoirs in areal extent simulated with W2, the irregular shape of Gatun Lake was captured by dividing the system into a number of branches which were similar in size to previous W2 applications.

Both Gatun Lake and Lake Madden were calibrated using a non-synoptic data set compiled from various sources and time periods. Seasonal averages of observed water column concentration data from a sampling study conducted for the years 1972-1974 were used to "calibrate" the model. Attempts to locate the original data were unsuccessful as the records of the original data had been destroyed. Separate calibrations for Gatun Lake and Lake Madden were accomplished using the previously mentioned seasonal observed data and a set of collection (seasonal, monthly, daily, synthetic) of flow and meteorological data. Model results were not perfect but, considering the lack of input information and the inconsistency between the forcing functions (meteorology and inflows) and the summary nature of the observations, the model calibration was deemed adequate for scenario testing.

A total of six W2 scenario simulations were made based upon the HEC-5 reservoir operation simulation results supplied by ACP. Four W2 simulations were made for the proposed Rio Indio reservoir and two for Gatun Lake. HEC-5 simulation results supplied by ACP provided the inflow, discharge, and water demand requirements for these scenarios. A four-year period selected from the HEC-5 simulation results supplied by ACP for use in these scenarios runs. The "lumped" information supplied by the HEC-5 output required some interpretation to assign it to appropriate inflows and discharges in W2. For example, HEC-5 reported inflows only as "local inflow" without regard to the source of the inflow. For W2, the "local inflow" had to be assigned to individual tributaries based upon relationships developed in this study.

Results of these scenarios indicated that water quality in the proposed Rio Indio reservoir as expressed by dissolved oxygen varied with the processes occurring in the reservoir. When the reservoir was being drawn down, either via inter-basin transfer or downstream discharge, the dissolved oxygen levels were higher. When the reservoir was being filled, undesirable low dissolved oxygen levels occurred in the bottom portions of the reservoir. These low dissolved oxygen episodes ended as soon as the reservoir started drawing down again. The reason for these low bottom water dissolved oxygen level was the sediment oxygen demand. Under filling conditions, there is less movement in the lower layers than there is when the reservoir is being drawn down. Consequently, there is less mixing and dilution of the lower dissolved oxygen water when the reservoirs are filling.

Single port and multi-port discharges were simulated for the proposed Rio Indio reservoir. These simulations were conducted to serve as a screening level assessment of the need for selective withdrawal. Single port withdrawals, whether for downstream discharge or inter-basin transfer, resulted in more water being withdrawn from the lower levels which aided in the mixing and dilution of the low dissolved oxygen by entrainment of waters from overlying layers that had higher dissolved oxygen levels. The cause of the low dissolved oxygen water in the lower layers was the sediment oxygen demand. When multi-port withdrawals were used, there was less mixing of the low dissolved oxygen waters. This resulted in the dissolved oxygen levels in the lower layers of the reservoir decreasing.

Multi-port discharges at the dam would be of benefit during period when the reservoir is being filled and the only discharge are the regulatory flows. Dissolved oxygen levels at the 12 m port for downstream releases tended to be very low during this period. Without the ability to with draw from other layers or some form of mechanical reaeration, this situation could result in the release of low dissolved oxygen water which could have detriment effects downstream. During the four year simulation, dissolved oxygen levels dropped to near 0 mg/l during the first year and below 2 mg/l for periods of the remaining years. Under such conditions, sediment releases of reduced metals could occur. Waters containing these metals, when oxygenated by passage through the dam, would precipitate metals in the channels downstream of the dam

The need of multi-port intakes for the inter-basin transfer tunnel is less dramatic. Results indicate little variation between the conditions at the tunnel intake site for the four scenarios performed. In actuality, the worse dissolved oxygen conditions occurred when the transfer flow was split between the three ports. Again this was due to there being less flow in the bottom layers which resulted in less vertical mixing. The anoxic conditions remained beneath the elevation of the lower tunnel intake. Dissolved oxygen levels increased when inter-basin transfers occurred due to the increased vertical mixing and movement of the waters. From this it appears that the critical condition will be when inter-basin transfers are commencing. After that initial "flush," the large flows will mix the reservoir and improve dissolved oxygen levels throughout the layers used for withdrawal.

Two scenarios were run for Gatun Lake, one in which a single port was used for the transfer flow intake and another in which three ports were used for the transfer tunnel intake, simulating the receipt of inter-basin transfers from Rio Indio reservoir. Results indicated little difference in the dissolved oxygen levels for the water intakes. This was expected for two reasons. One, the water quality of the tunnel discharge was similar whether single port or multi-port withdrawal was used at the tunnel intake. Second, all major intakes are far removed from the tunnel discharge site and are negligibly impacted by it. Only the intake at Escobal is on the same branch as the tunnel discharge site. It is located approximately 14 miles from the discharge site. Dissolved oxygen levels at the Escobal intake were high in both scenarios. No allowances were made in the Gatun scenarios for reaeration resulting from energy dissipation devices such as baffle blocks.

Recommendations

The following recommendations have been developed during the course of this study and are presented here as aids for further studies of the Panama Canal system.

a. Observed data. The data set used for this study was the best that was available at the time. Creation of an up to date database consisting of water column observations, tributary concentrations, and tributary inflows should be a top priority. Such a database would allow refinement of the models developed and increase the belief in the model's relevance. Observation of currents and collection of current/flow data in selected locations of Gatun Lake would aid in determining the occurrence and assessing the impact of non-uniform flows. The data base generated by this effort would enable ACP to improve the hydrodynamic and water quality simulation model developed in this task.

b. Watershed loads and conditions. ACP has indicated that the population along the Transithmian Highway has increased substantially in the years since the 1972-1974 water quality sampling study. Consequently, it is also felt that there is also an increase in loadings associated with this growth. Estimation of the impact of this growth upon the water of Gatun Lake, Lake Madden, and the proposed reservoir at Rio Indio requires a comprehensive approach consisting of sampling, hydrology, and application of watershed models to assess the loads reaching the tributaries and lakes.

c. Sediment processes. Scenarios for Rio Indio indicated the significance of good estimates for sediment oxygen demand. In the Rio Indio scenarios, anoxic and hypoxic bottom water conditions were observed. These conditions in the model are a result of the specified SOD rate and have a direct impact on the requirement for inter-basin selective withdrawal capability. The rate used was a conservative value. However, there is no information as to what the appropriate SOD ate should be. Soil samples should be collected at the proposed Rio Indio reservoir site and analyzed for SOD and sediment releases. Based upon these results, the scenarios for Rio Indio should be reassessed using the revised SOD rates.

d. Ongoing monitoring. A limited continuing sampling effort at key locations in the system will enable earlier detection of changes in water quality. The data collected would serve a "first warning" for water quality degradation. It would aid in the analysis of "cause and effect" of water quality problems. Development of a monitoring program would enable ACP to be pro-active when dealing with water quality problems instead of reactive.

e. Dam site selective withdrawal capability. The Rio Indio Reservoir simulations indicate the need for selective withdrawal at the dam site. During periods where only minimum flows were simulated, low dissolved oxygen conditions existed near the lower port simulated (12m). The ability to draw waters from different levels would enable waters of different qualities to be mixed thereby increasing the quality (as indicated by dissolved oxygen) in the receiving waters.

f. Tunnel intake selective withdrawal capability. The requirement for a multi-port structure to support selective withdrawal is less clear for the tunnel intake. In the simulation where the multi-port facility was tested, dissolved oxygen levels were higher in the tunnel water during certain periods of tunnel operation, generally when the first transfers occurred. The lowest DO level predicted at the tunnel intakes was 2.33 g/m^3 for the simulation using only one intake port for the tunnel inlet. For the simulation performed with the tunnel flow split between three inlets, the dissolved oxygen was 3.11 at that same time. This dissolved oxygen level value is heavily dependent upon sensitivity of the SOD value used. It can be said that the dissolved oxygen levels were higher during the first portion of inter-basin transfer for simulations using a multi-port tunnel intake. After the initial portion of inter-basin transfer, the additional mixing in Rio Indio resulting from the inter-basin transfer flows resulted in tunnel intake dissolved oxygen levels being similar for the single port and multi-port intake cases. No allowance was made in the simulations for reaeration at the tunnel outlet. These simulations should be revisited once better information on SOD rates are obtained.

g. Additional scenarios. Two sets of conditions were tested during this study for inter-basin transfer flow and those only differed in the type of tunnel intake used (single or multi-level). It would be desirable to simulate other periods than the 1951-1954 period to see the impact that differing water levels in Rio Indio Reservoir had on transfer flow water quality.

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14. ABSTRACT
The Panama Canal Authority operates the Panama Canal that connects the Atlantic and Pacific Oceans across the isthmus of Panama allowing for the passage of ocean-going vessels. The canal has a length of 80 km and is capable of traversing vessels up to 294 m long with maximum drafts of 12 m. Most portions of the canal are above sea level in a man-made reservoir, Gatun lake. The Canal, its associated reservoirs, and the lands adjacent to them are administered by the Panama Canal Authority (ACP). ACP is currently investigating the feasibility of expanding the canal system by constructing additional reservoirs to increase water availability for navigation. Currently, Gatun Lake and Lake Madden produce adequate quantities of water for navigation, power generation, and water supply. However, there is concern that an increase in the number of ships using the Canal in the future, coupled with drier conditions, could result in situations where there is inadequate water for canal operations. ACP is studying up to three new reservoirs to the west of Gatun Lake. The reservoirs of the western watershed are Río Indio, Caño Sucio, and Coclé del Norte (or Toabré). Waters from these reservoirs would be transferred via channel and tunnel to Gatun Lake. The purpose of this study was to assess what the expected water quality would be in the proposed reservoirs of the western watershed and what might occur due to interbasin water transfers from the proposed reservoirs to Gatun Lake with respect to the existing water quality. This report discusses the modeling results and offers conclusions and recommendations on the various scenarios simulated.

15. SUBJECT TERMS

CE-QUAL-W2	Coclé del Norte	Panama Canal
Caño Sucio	Gatun	Water quality modeling
	Madden	

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